



Robust ABF for Large, Passive Broadband Sonar Arrays

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Introduction: Themes



ABF for large arrays ($100 < N < 10000$ elements) require particular attention to computing efficiency

- Element space $\text{DMR} > O(ND^2)$

“Ideal” reduced complexity adaptive beamformer:

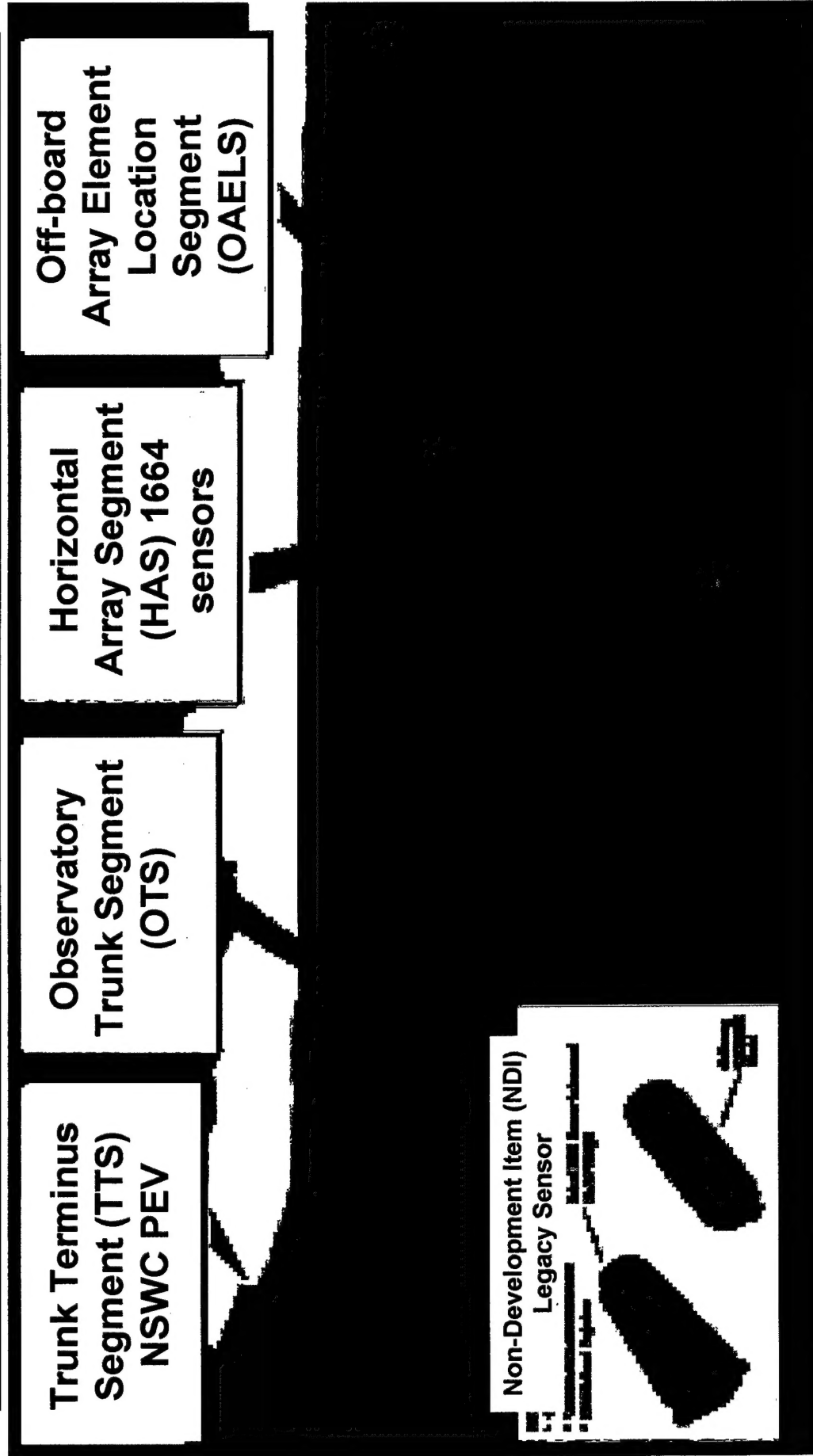
- Adaptation space dimension, N_a , close to required adaptive degrees of freedom D
- Consistent with spatial sampling theory
- Steering direction invariant
- “Robust robustness”

Broadband beamforming:

- computing efficiency inherent at low frequency
- can trade high SNR signal suppression for spatial resolution



LOPS AO Array Wet Subsystem(AWS)

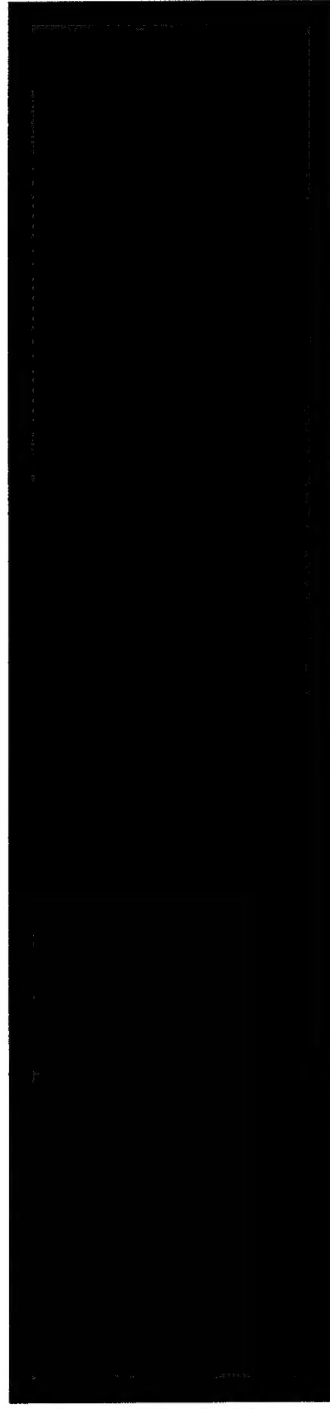


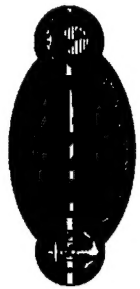


Complexity (C) in Dominant Mode Rejection (DMR) Adaptive Beamforming (ABF)

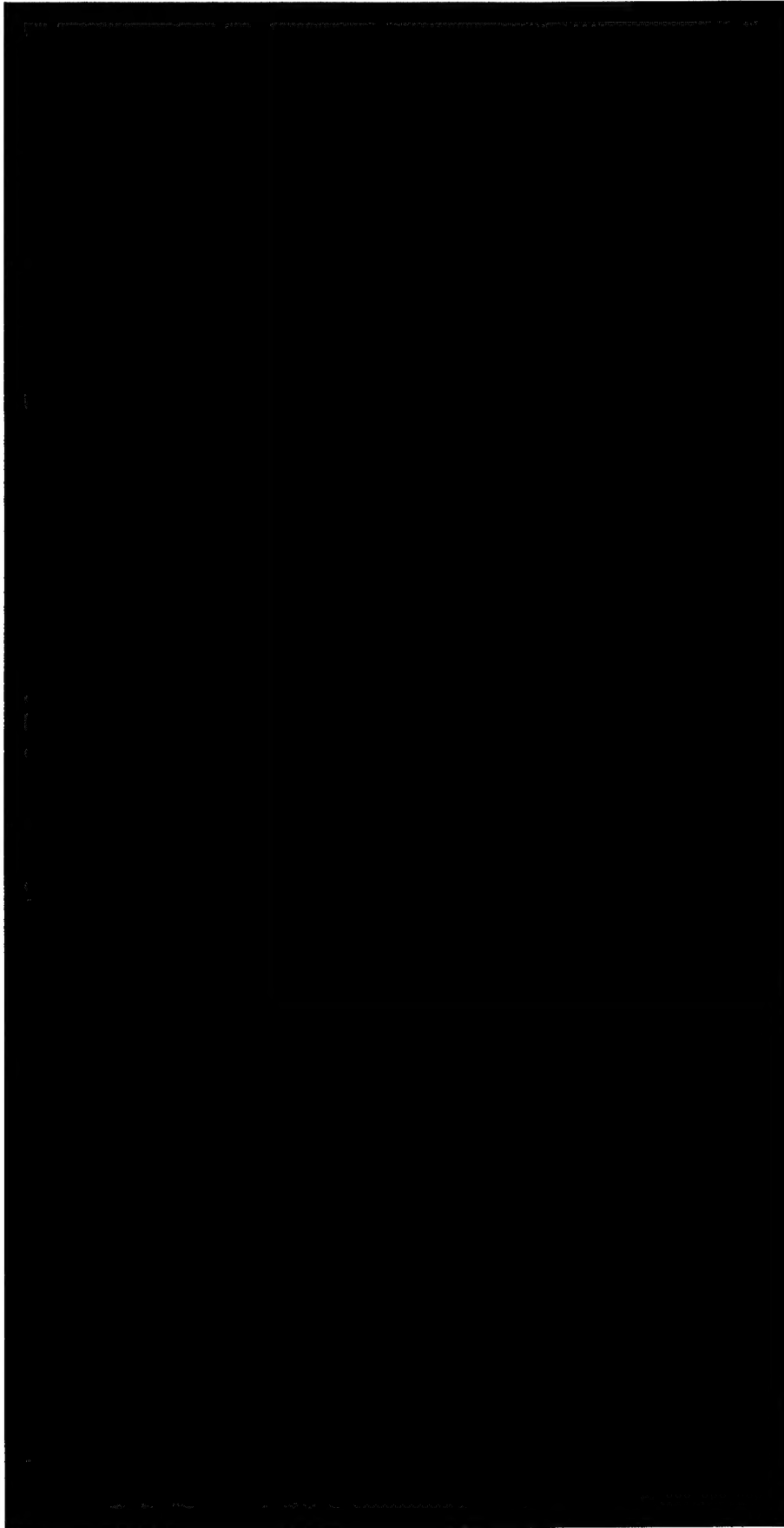


- N = number of sensors
- S = number of steering directions
- N_a = number of adaptively filtered channels
- D = number of adaptive degrees of freedom



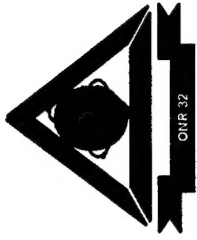


Candidate ASAP Methods for Large BB Arrays

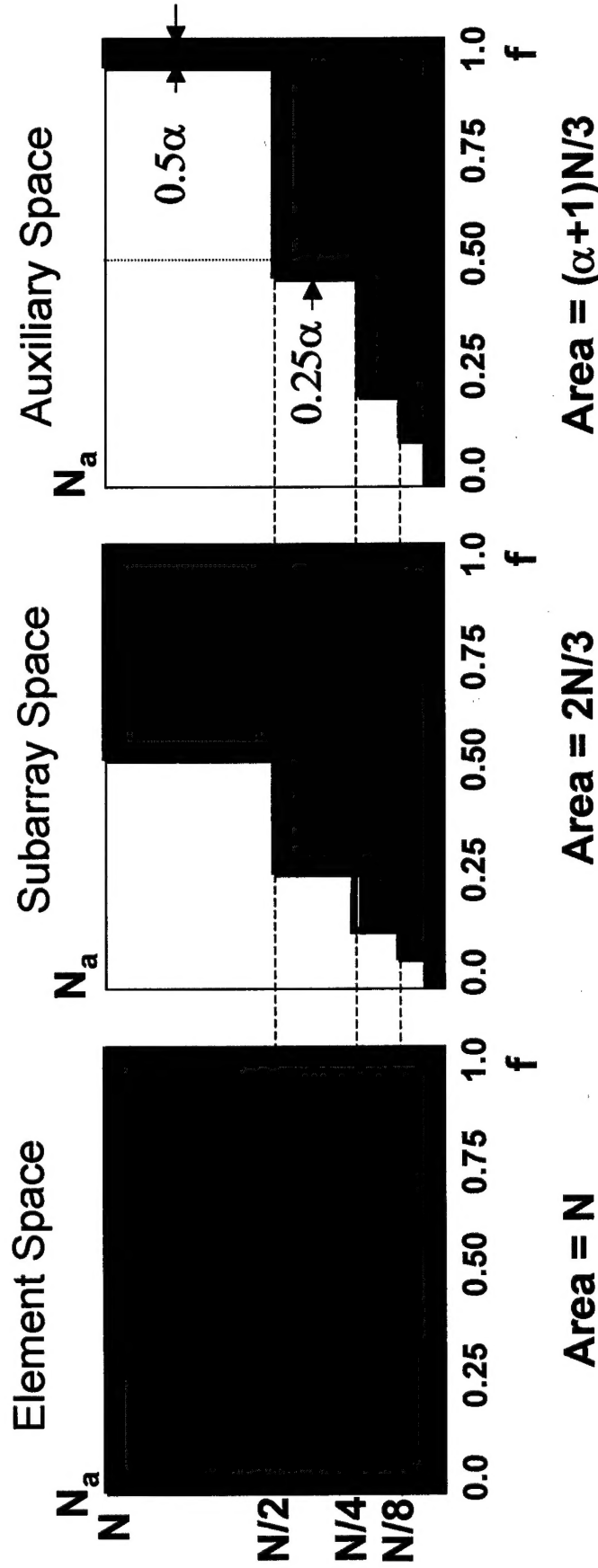




Adaptive Degrees of Freedom: Frequency Dependence



N = number of sensors $\lambda/2$ spaced sensors in linear array
 N_a = number of adaptive channels
 f = frequency normalized by the $\lambda/2$ spacing design frequency
 $f=1$ is array design frequency



$N_a = N_a(\text{Number of Sources, Number of } \lambda/2\text{-s in Aperture) (???)$



Measures of Performance

- Qualitative: Bearing-Time-Recording (BTR)
side-by-side beauty contest
- Quantitative: Array Gain (AG)



$\mathbf{w}(\theta_{\text{targ}})$ = beamforming filter vector for beam steered at θ_{targ}

$$\begin{aligned} \mathbf{P}_{\text{true}}(\theta_{\text{targ}}) &= \text{Cross-Channel Spectral Density Matrix (CSDM)} \\ &= \mathbf{d}(\theta_{\text{targ}})\mathbf{d}(\theta_{\text{targ}})^H, \quad \text{Trace}(\mathbf{P}_{\text{true}}(\theta_{\text{targ}})) = N \end{aligned}$$

$$\begin{aligned} \mathbf{Q}_{\text{true}}(\text{all } \theta \neq \theta_{\text{targ}}) &= \sum_m \alpha_m \mathbf{d}(\theta_m)\mathbf{d}(\theta_m)^H + \alpha_0 \mathbf{I}_N, \\ \text{Trace}(\mathbf{Q}_{\text{true}}(\theta_{\text{targ}})) &= N \end{aligned}$$



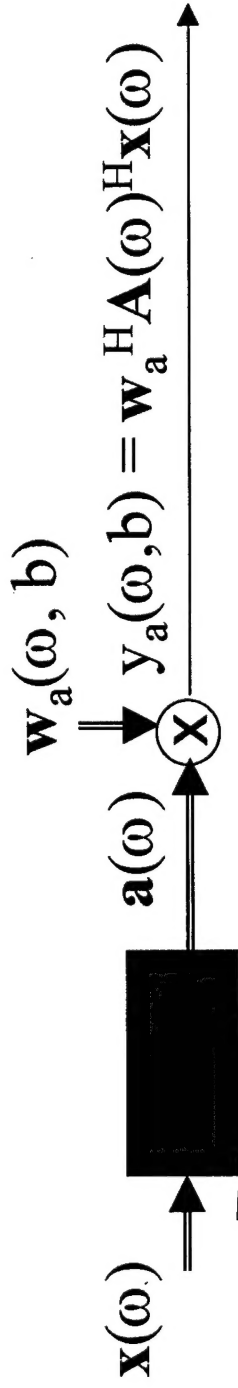
AG MOP Usage



- AG is given as a function of θ_{targ} for static source examples
- AG is given along the bearing track of a clairvoyant designated target tracker for dynamic source examples



ABF with Subarray Preprocessing



Steering invariant subarray grouping:

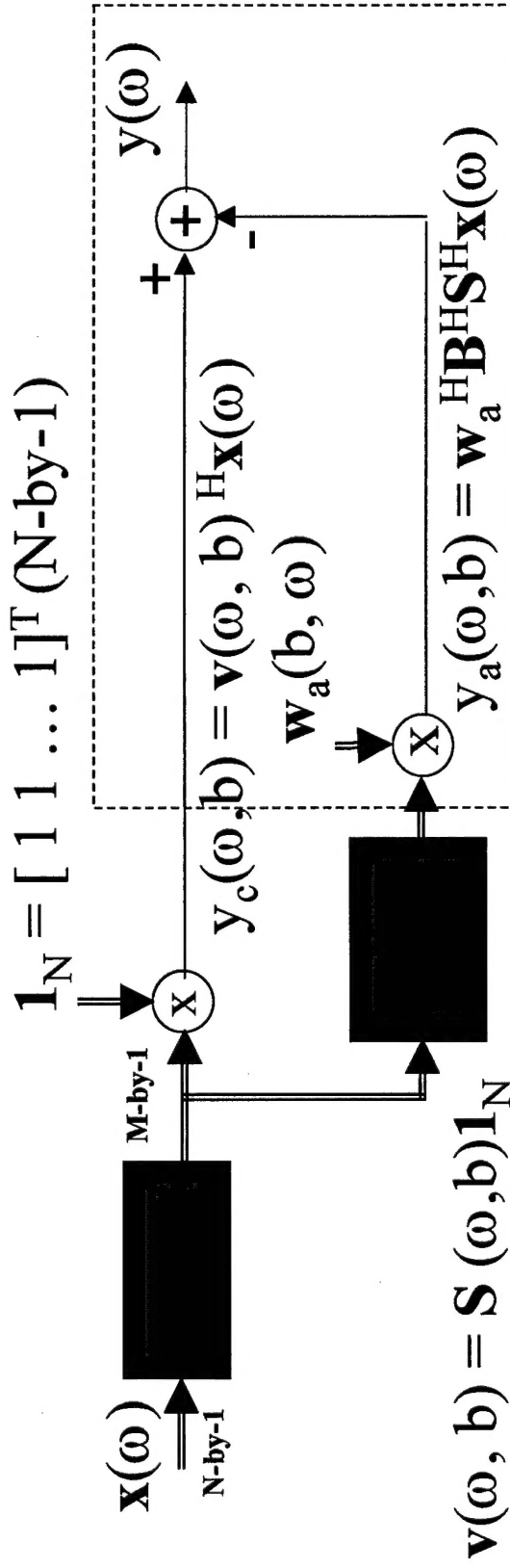
$$v_a(\omega, b) = A(\omega)^H v(\omega, b)$$

Suppress ω and b notation:

$$w_a = \frac{1}{v_a^H R_{aa}^{-1} v_a} R_{aa}^{-1} v_a$$



GSC with Presteering and Signal Blocking Distortionless Response (DR)



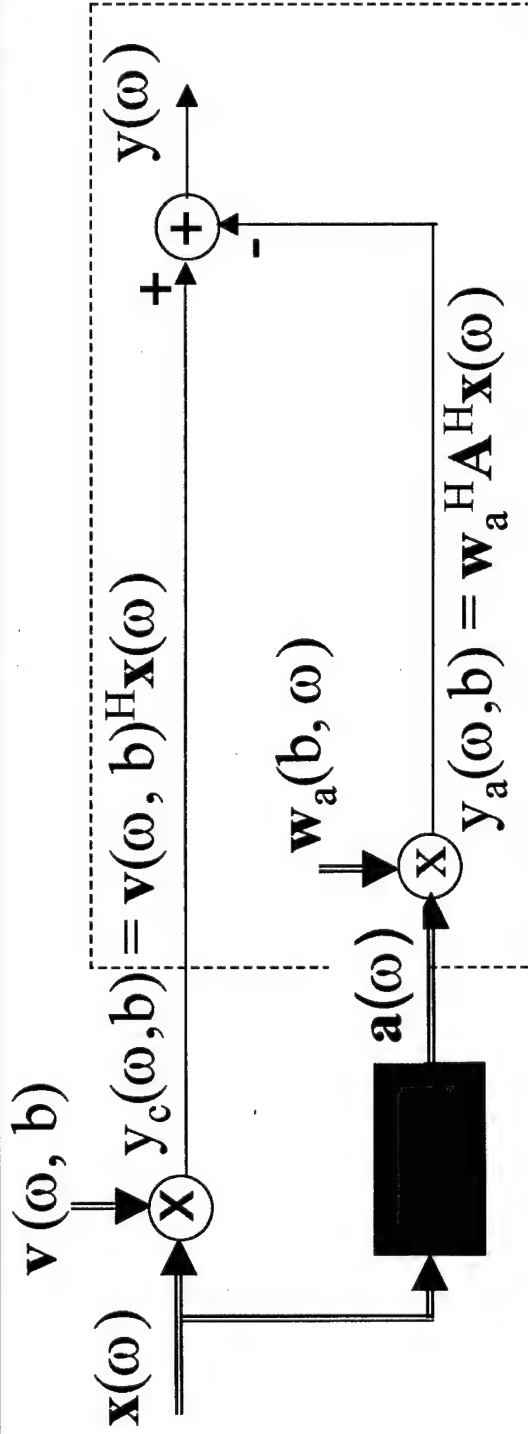
Suppress ω and b notation:

$$\mathbf{B}^H \mathbf{1}_N = \mathbf{0}_M = [0 \ 0 \ \dots \ 0]^T \ (M-by-1)$$

$$\mathbf{w}_a = [\mathbf{B}^H \mathbf{S}^H \mathbf{R}_{xx} \mathbf{S} \mathbf{B}]^{-1} \mathbf{B}^H \mathbf{S}^H \mathbf{R}_{xx} \mathbf{v}$$



Steering Invariant DR Sidelobe Cancellation (SISC) Process



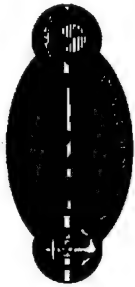
Constrained
Weiner Filter

$$v_a(\omega, b) = A(\omega)v(\omega, b)$$

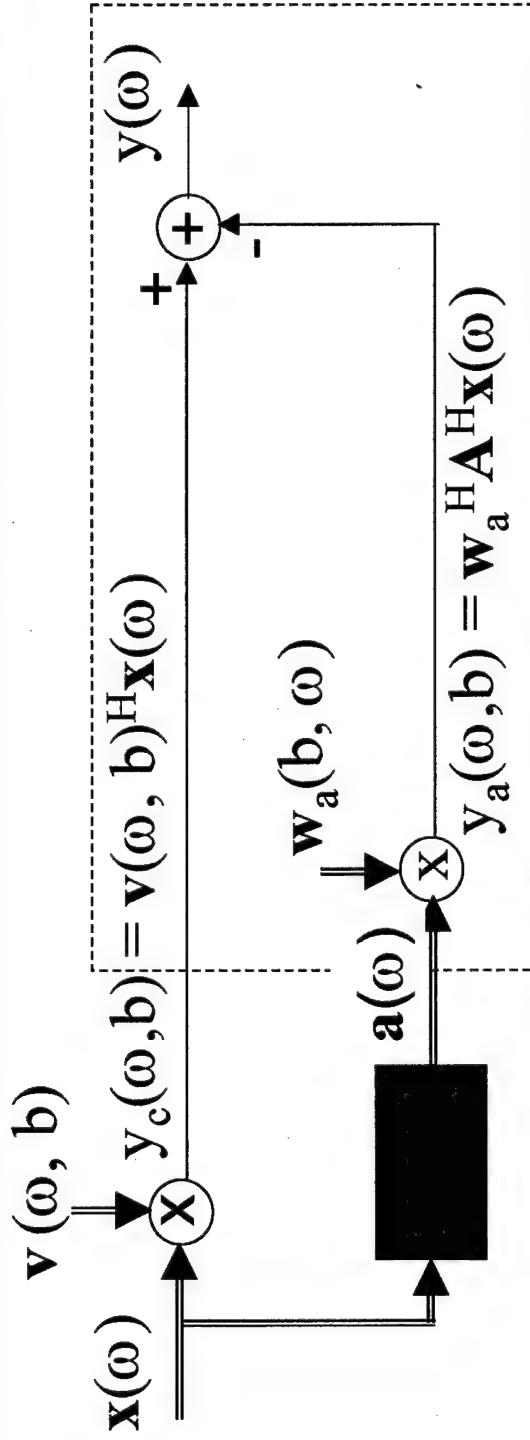
Suppress ω and b :

$$w_a = R_{aa}^{-1} \left(r_{ac} - \left(\frac{r_{ac}^H R_{aa}^{-1} v_a}{v_a^H R_{aa}^{-1} v_a} \right) v_a \right)$$





Steering Invariant DR Sidelobe Cancellation (SISC) Process

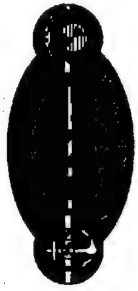


Constrained
Weiner Filter

$$\mathbf{v}_a(\omega, b) = \mathbf{A}(\omega) \mathbf{v}(\omega, b)$$

Suppress ω and b :

$$\mathbf{W} = \frac{\mathbf{V} - \mathbf{A} \mathbf{W}_a}{1 - \mathbf{W}_a^H \mathbf{A}^H \mathbf{V}} \quad \text{with} \quad \mathbf{W}_a = \mathbf{R}_{aa}^{-1} (\mathbf{r}_{ac} - \alpha \mathbf{v}_a)$$



Robust Robustness (RR): Robustness Management



CBF (\mathbf{v}) and unconstrained ABF (\mathbf{w}_0) linear blend

$$\mathbf{w} = (1 - \beta) \mathbf{v} + \beta \mathbf{w}_0,$$

where on a beam-by-beam as-needed basis (RR),

$$\beta = \begin{cases} 1, & \text{for } |\mathbf{w}_0 - \mathbf{v}|^2 \leq G \\ \frac{G^{1/2}}{|\mathbf{w}_0 - \mathbf{v}|}, & \text{for } |\mathbf{w}_0 - \mathbf{v}|^2 > G \end{cases}$$

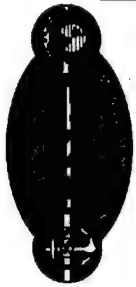
$$G = WNGC - 1.$$

For a Sidelobe Cancellation ABF

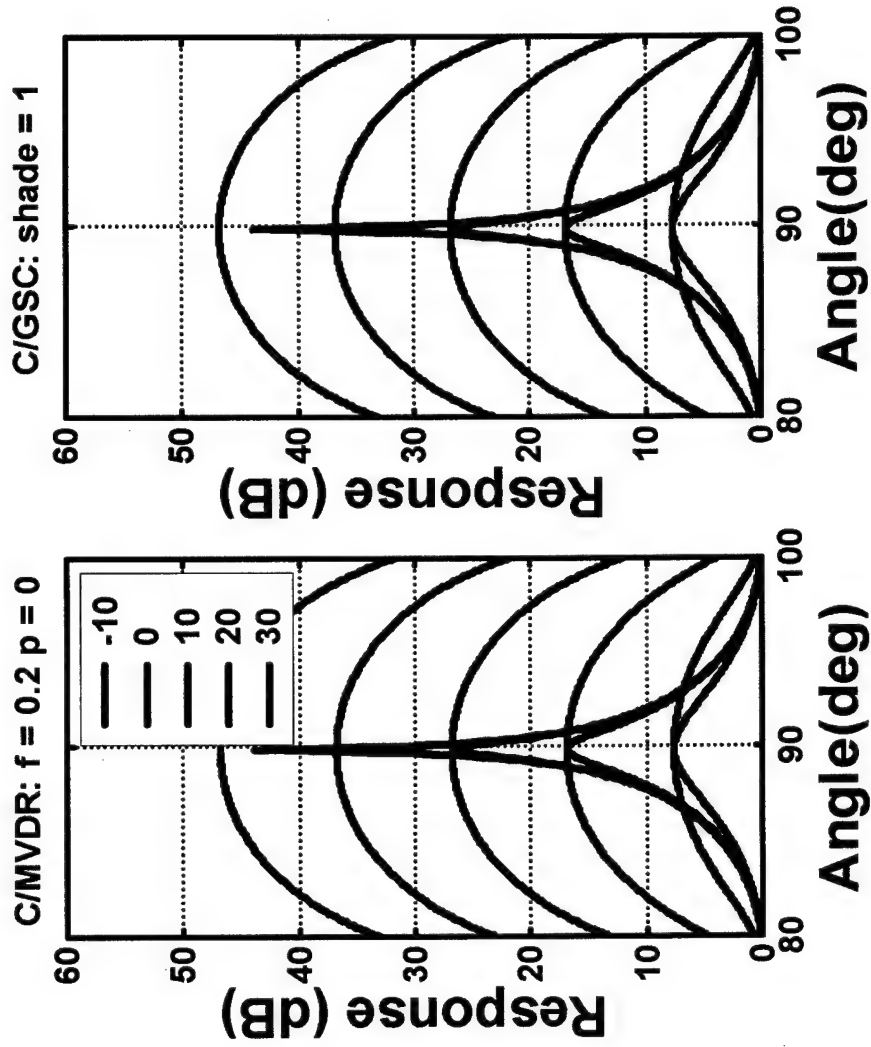
$$\mathbf{w}_0 = \mathbf{v} - \mathbf{A}\mathbf{w}_a$$

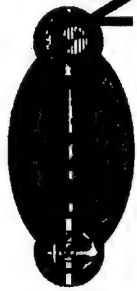
and the

$$\mathbf{w} = \mathbf{v} - \beta \mathbf{A}\mathbf{w}_a \text{ (really simple!).}$$



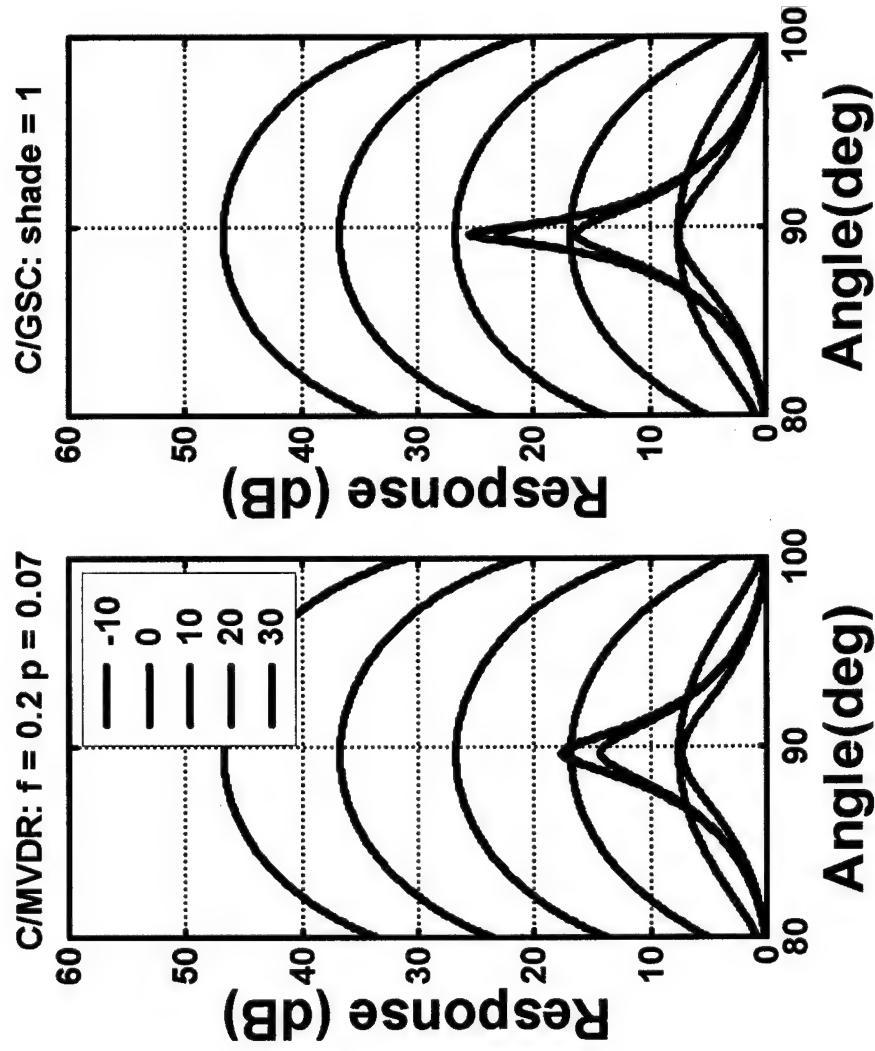
ESMVDR (I) and SI(G)SC w/o RR (r):
NumHydPerGroup = 6 (M = 8, N = 48, pert=0.)





ESMVDR (I) and SI(G)SC w/o RR (r):

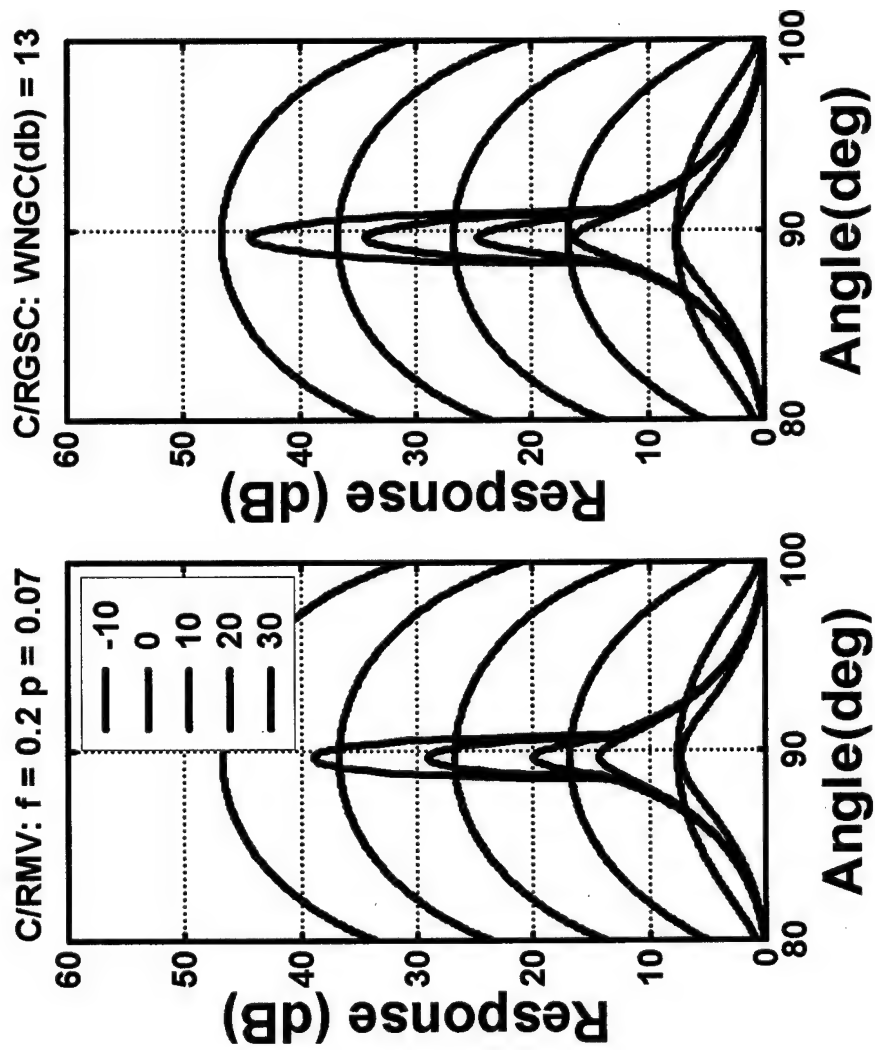
NumHydPerGroup = 6 ($M = 8$, $N = 48$, $\text{pert}=0.07$)

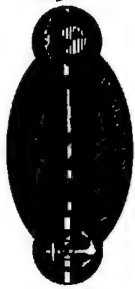




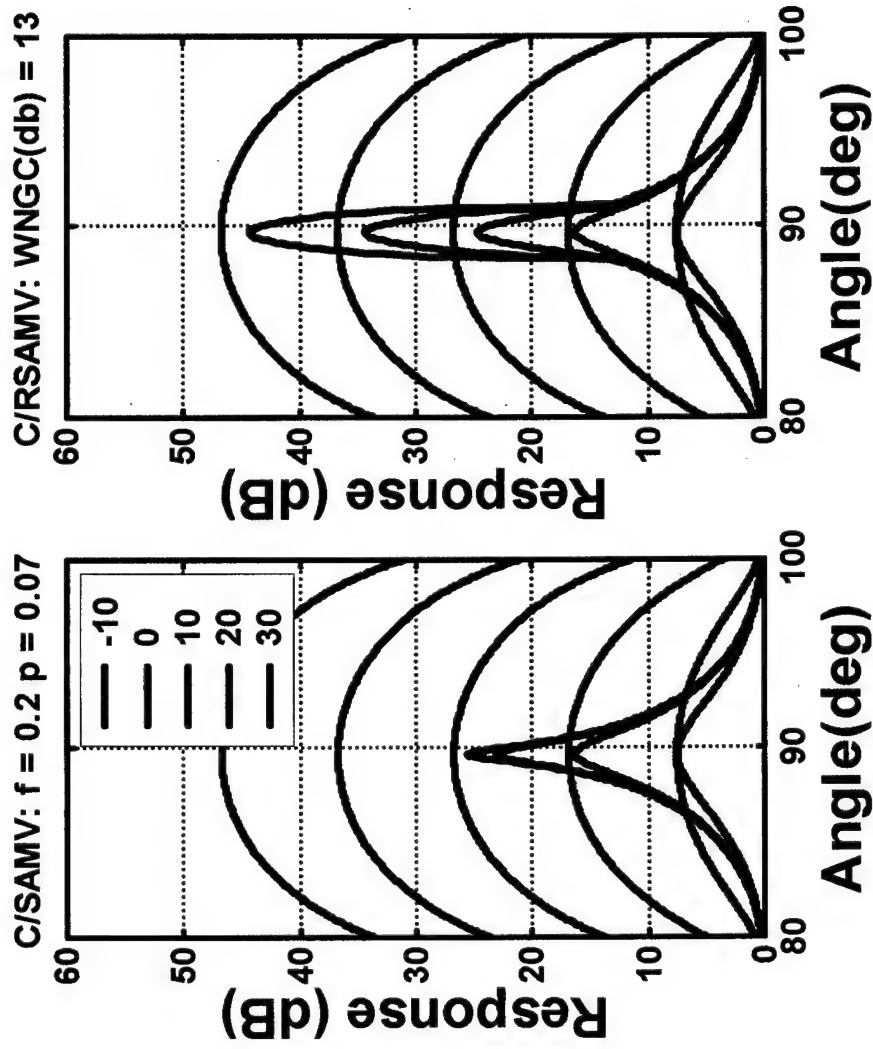
ESMVDR (I) and SI(G)SC with RR (r):

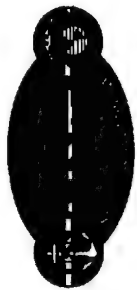
NumHydPerGroup = 6 ($M = 8$, $N = 48$, $\text{pert} = 0.07$)





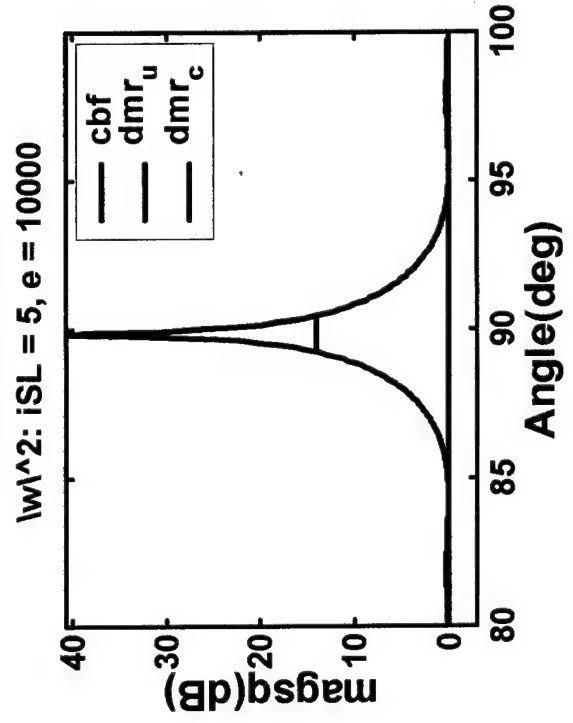
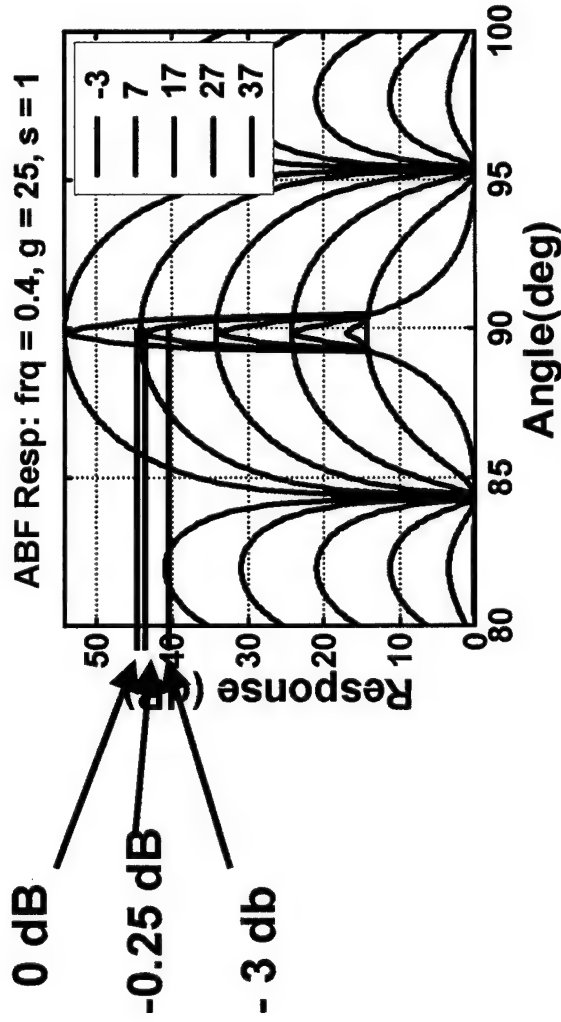
Subarray Preprocessing w/o (l) and with (r) RR: NumHydPerSA = 6 (M = 8, N = 48, pert=0.07)



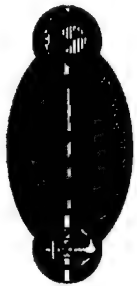


Blended CBF-DMR Point Design

(Owsley, SAM 02)

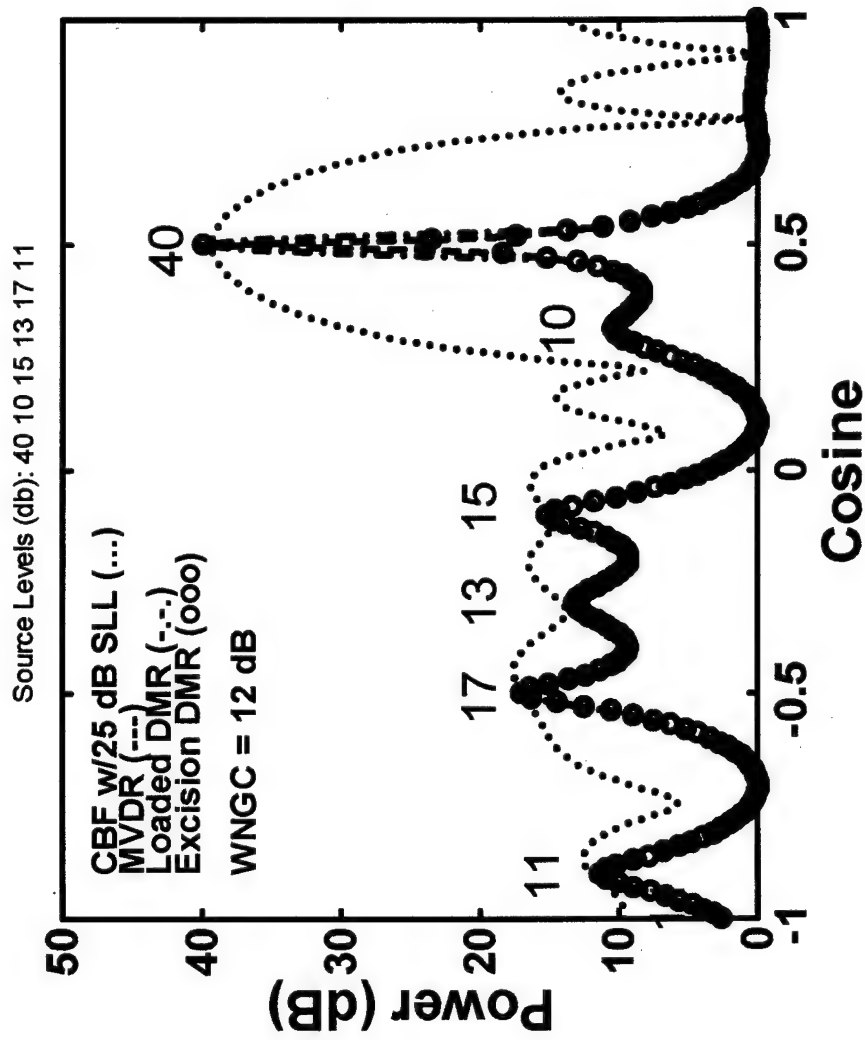


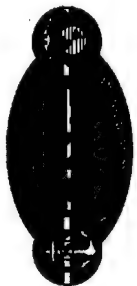
Design Procedure:
One step pre-resolution
for G in terms of
specified allowable
signal suppression v.
SNR.



Six Stationary Sources: ES

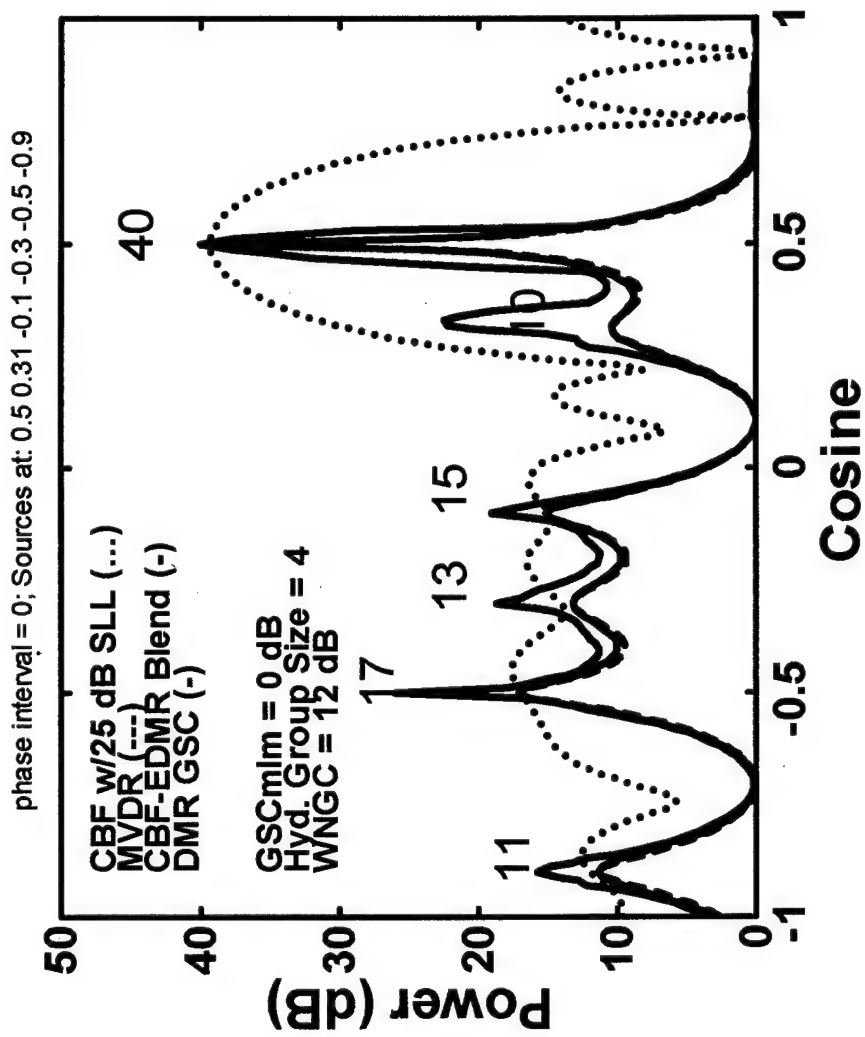
(pert = 0.0, N = 48, D = 7, f = 0.2, sa group size = 4)





Six Stationary Sources

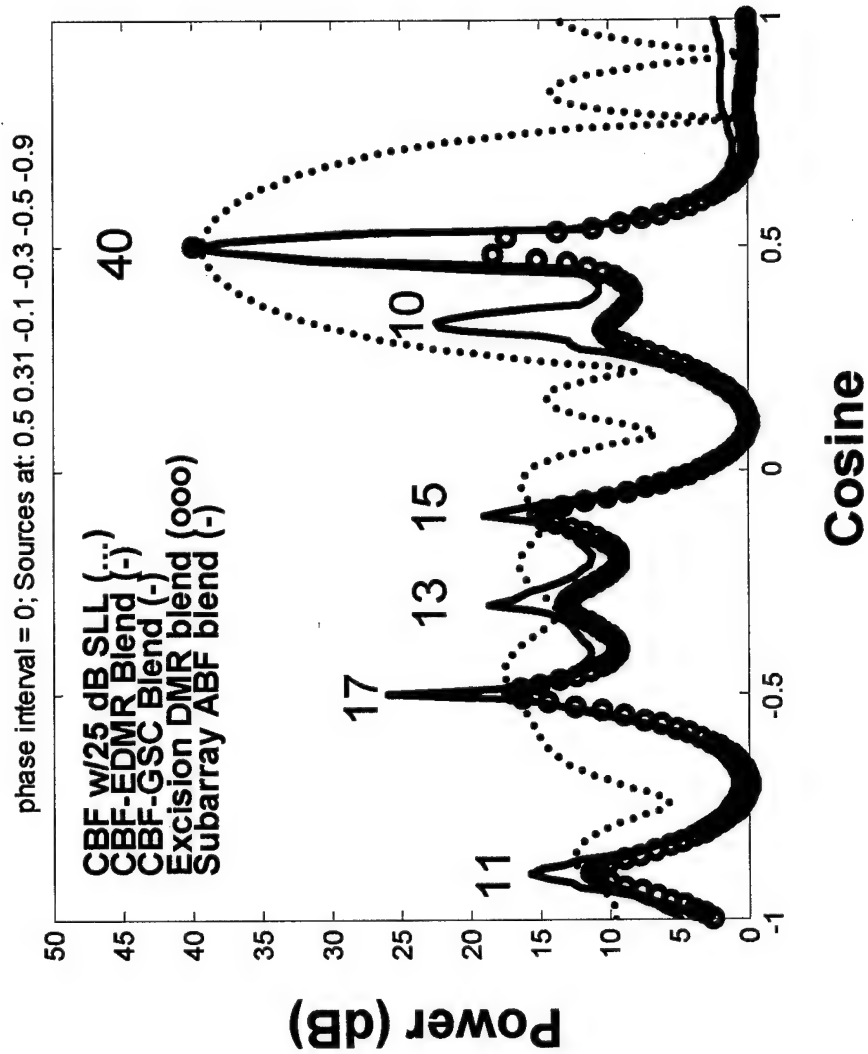
(pert = 0.0, N = 48, D = 7, f = 0.2, sa group size = 4)

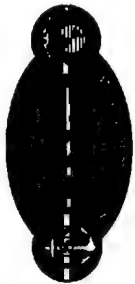




Six Stationary Sources

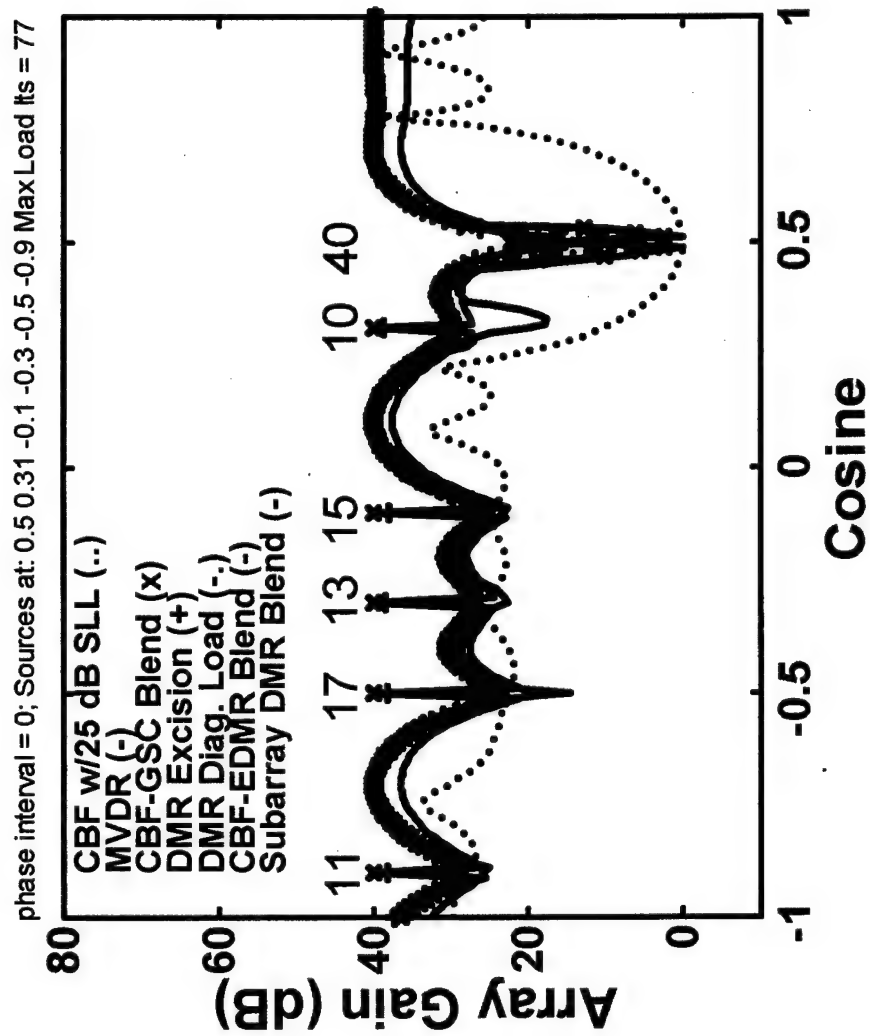
(pert = 0.0, N = 48, D = 7, f = 0.2, sa group size = 4)

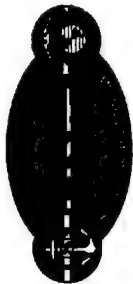




Six Stationary Sources

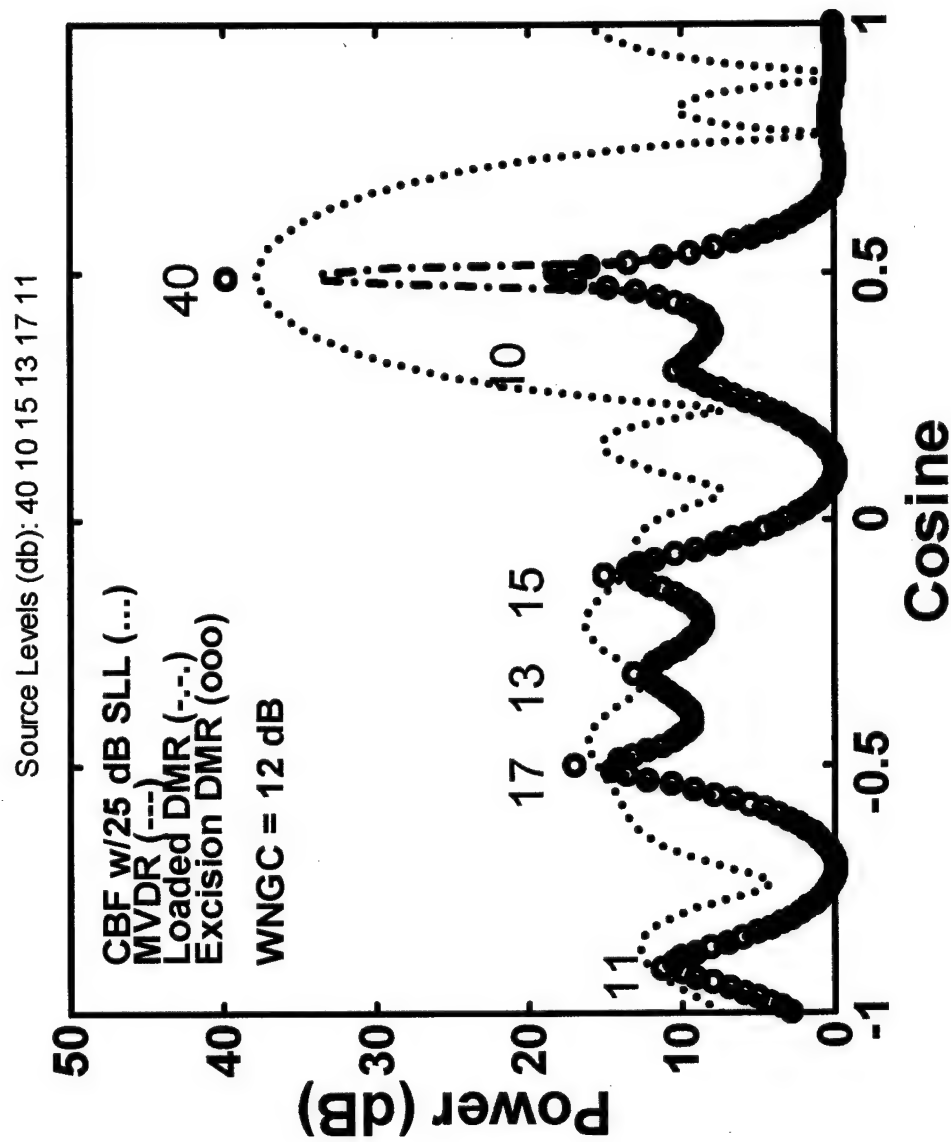
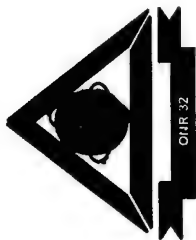
(pert = 0.0, N = 48, D = 7, f = 0.2, sa group size = 4)

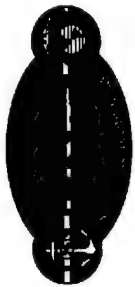




Six Stationary Sources

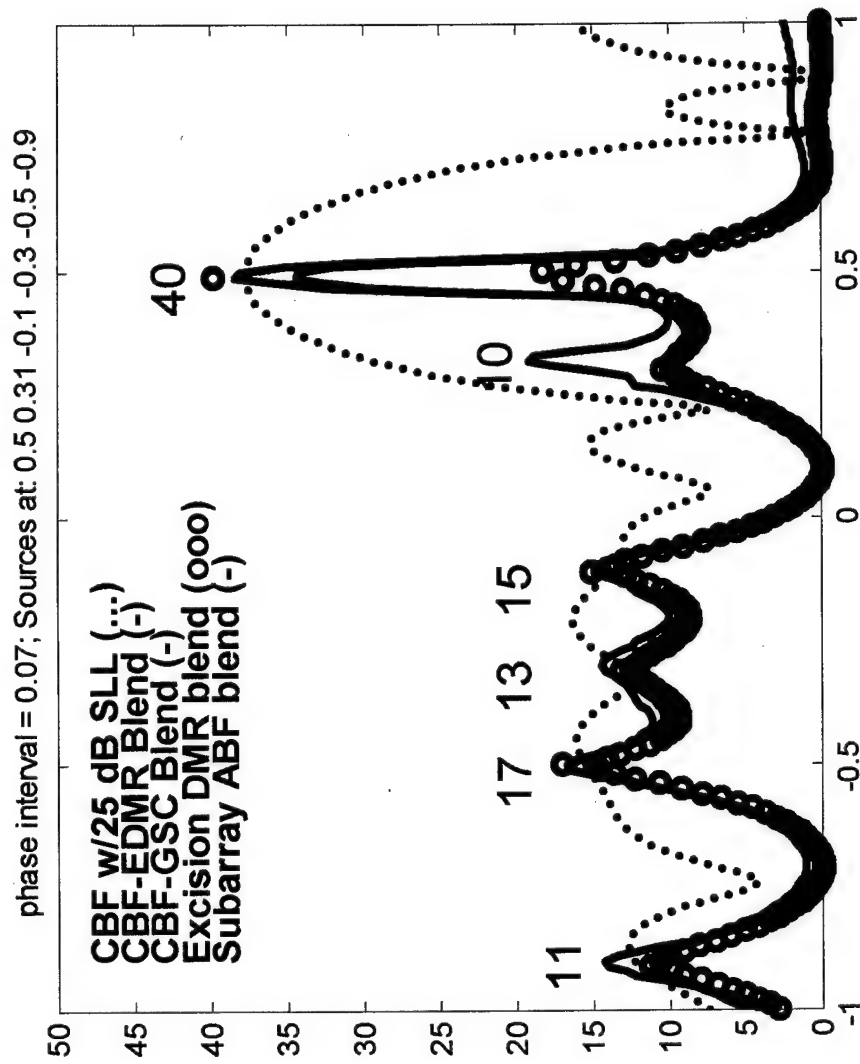
(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)





Six Stationary Sources

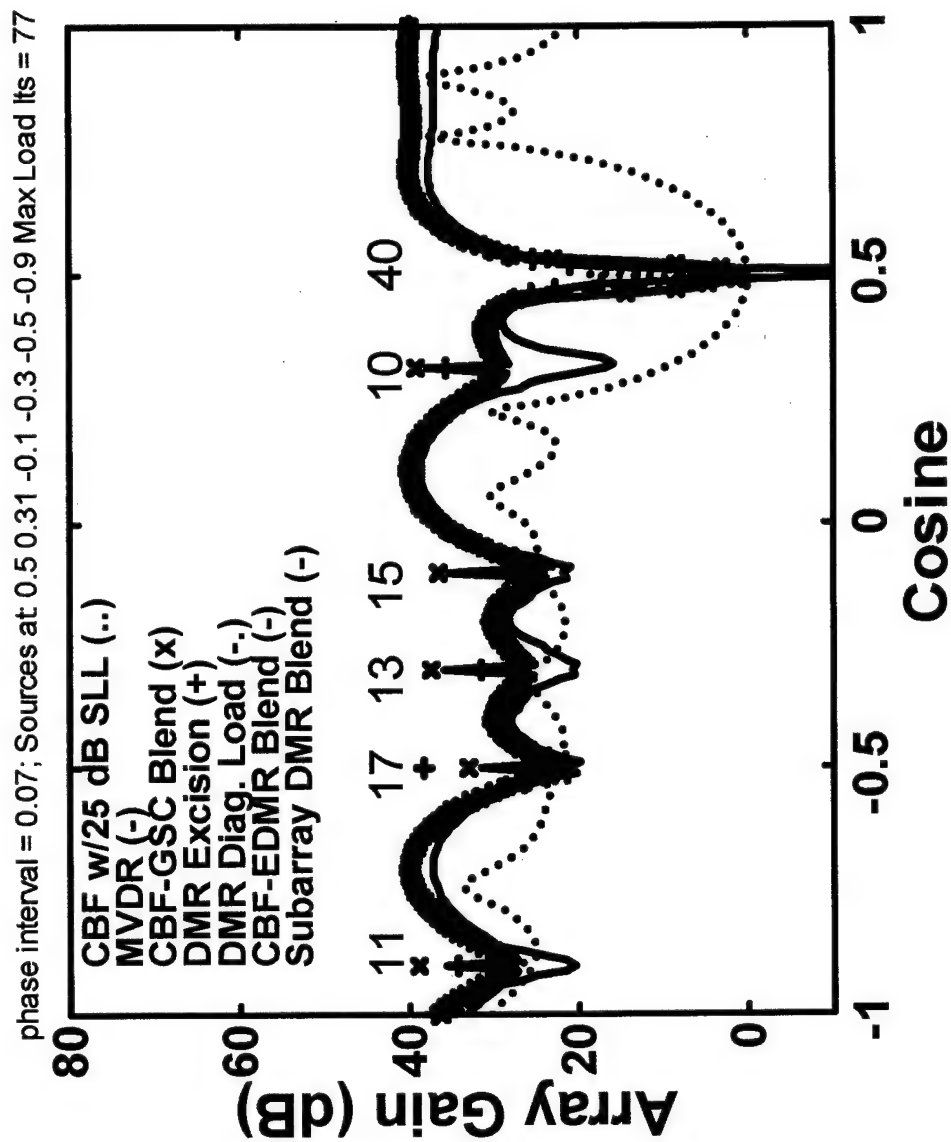
(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)





Six Stationary Sources

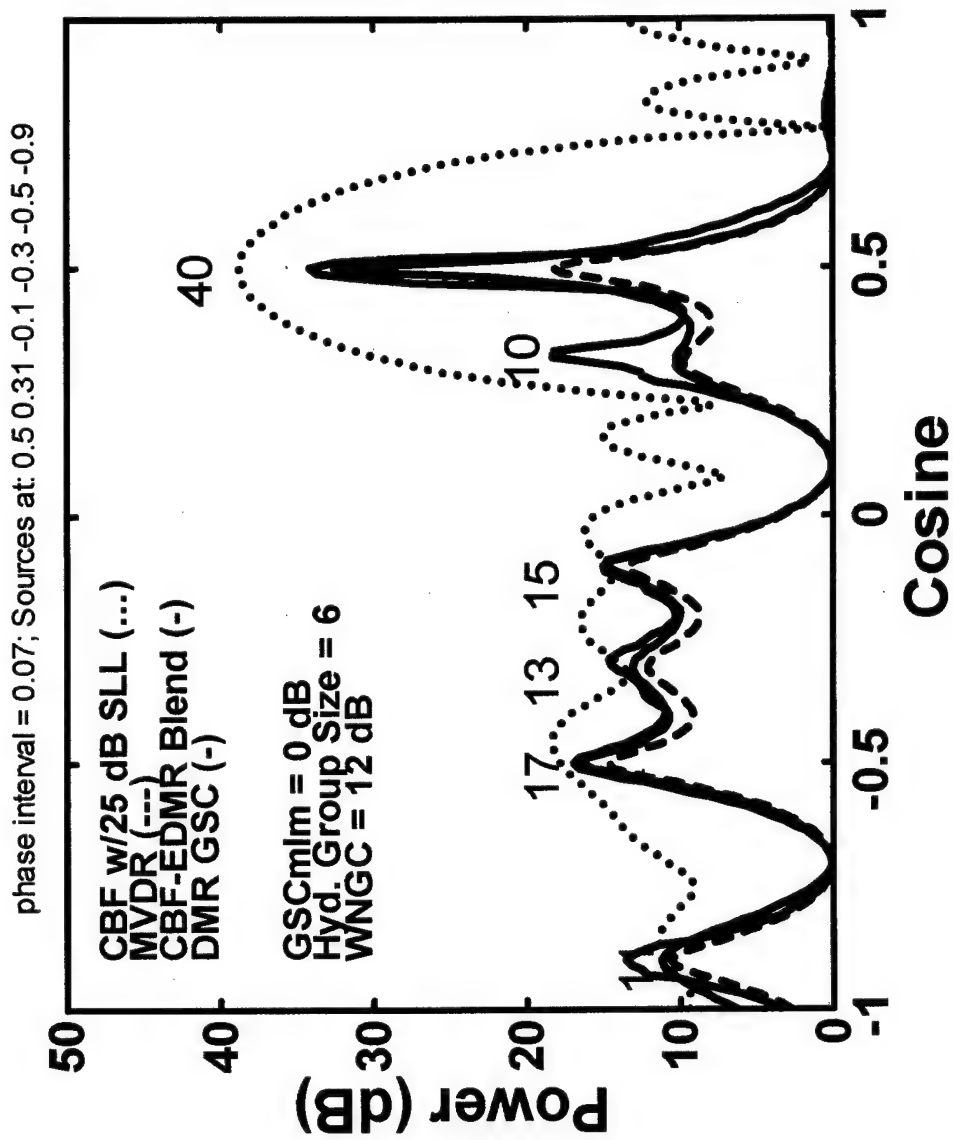
(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)





Six Stationary Sources

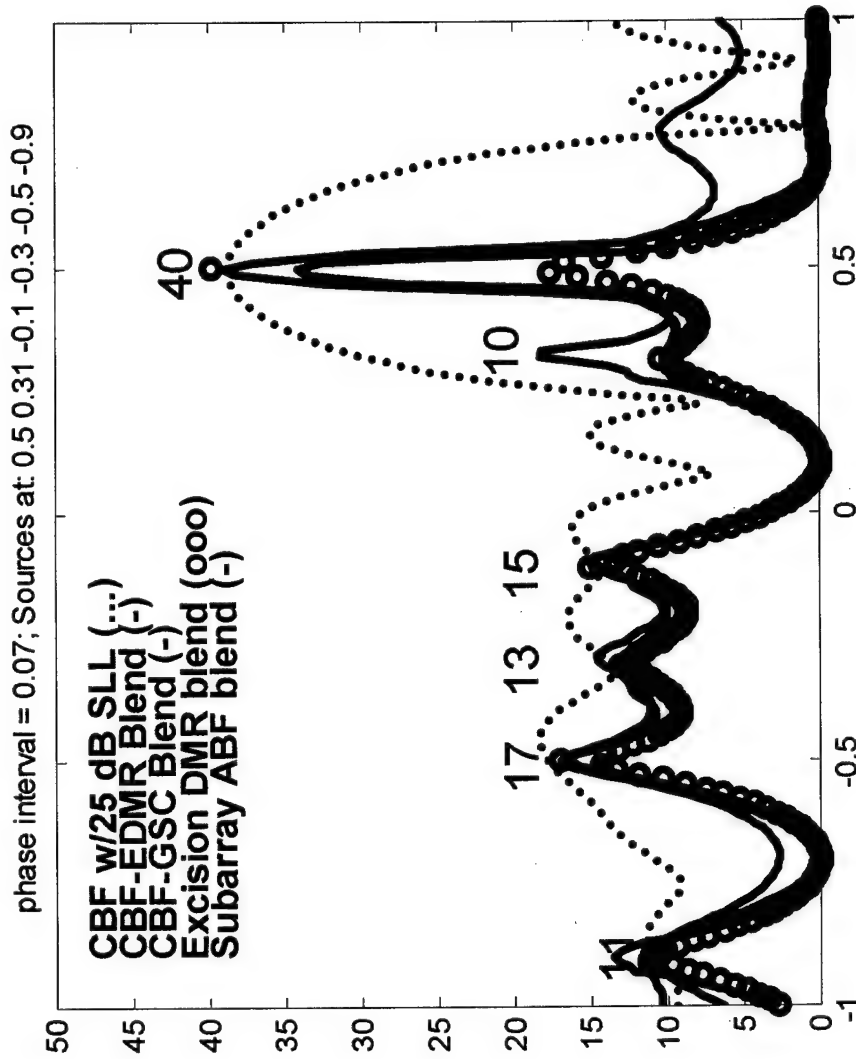
(pert = 0.07, N = 48, M = 8, D = 7, f = 0.2, number of sensors per sa = 6)





Six Stationary Sources

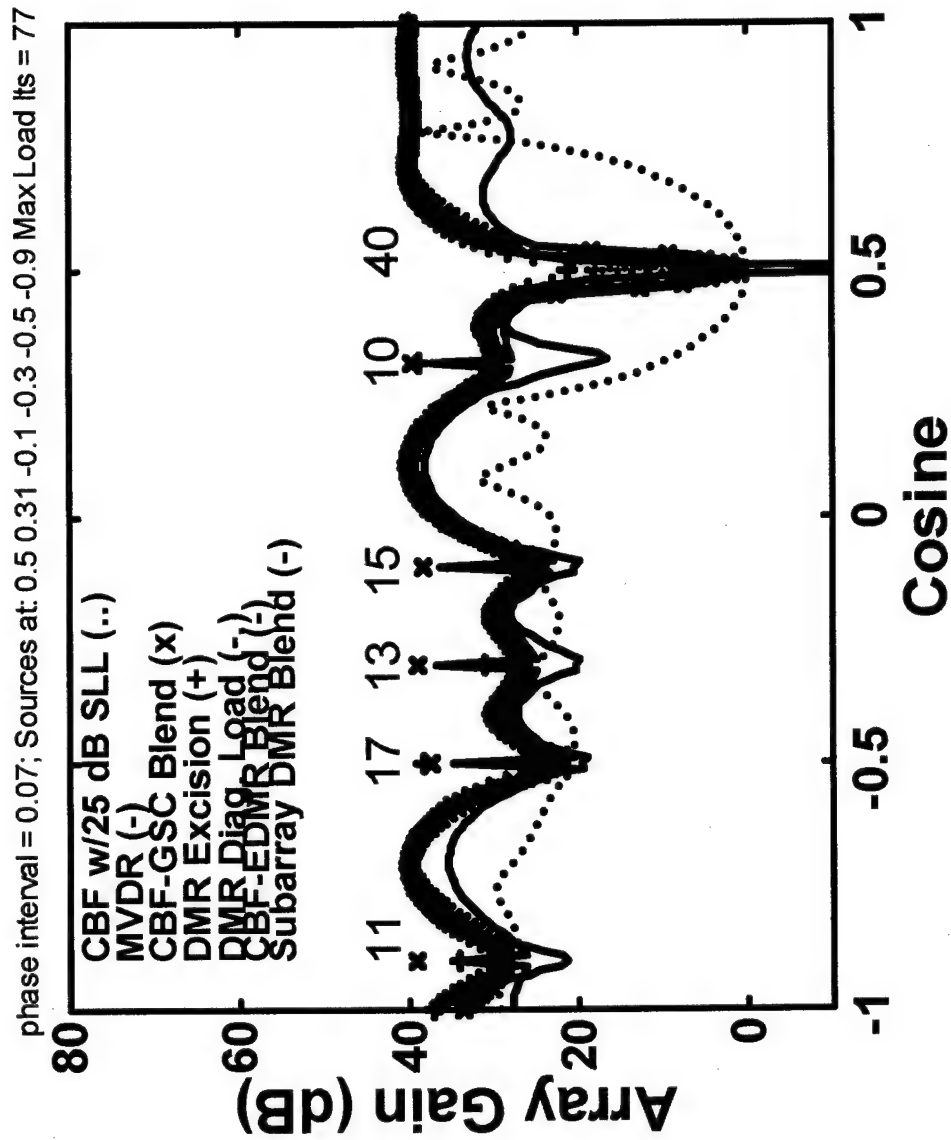
(pert = 0.07, N = 48, M = 8, D = 7, f = 0.2, number of sensors per sa = 6)

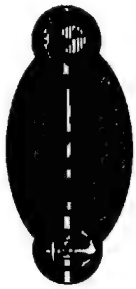




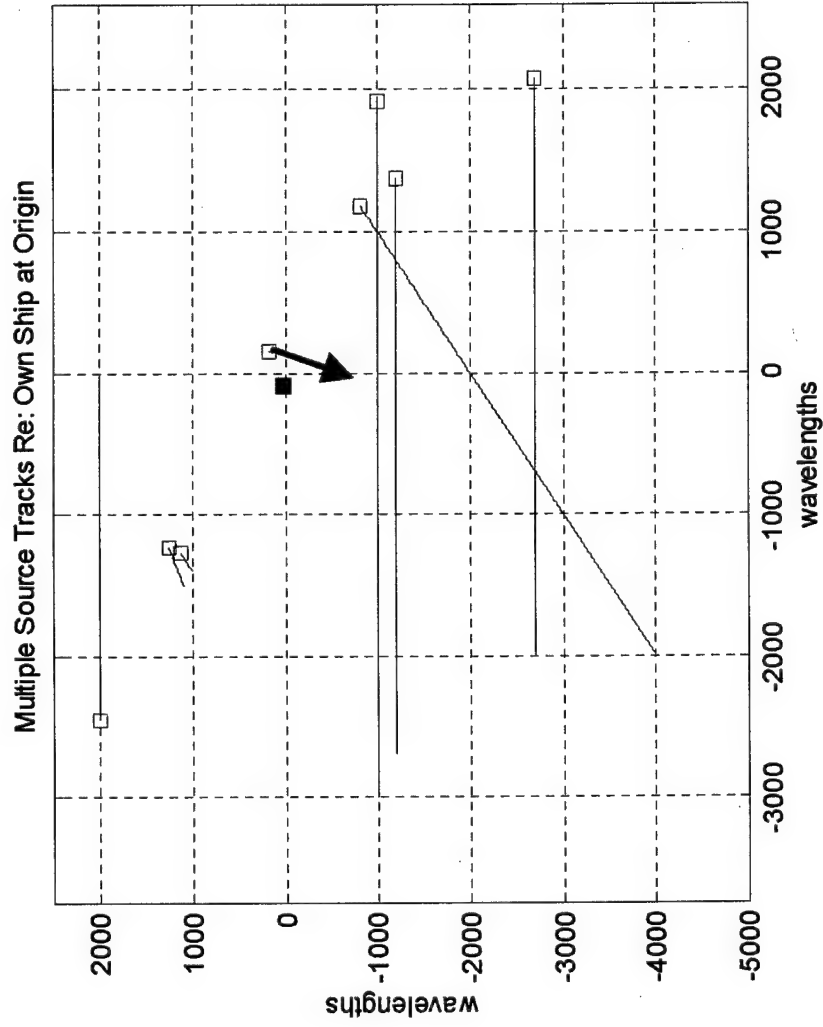
Six Stationary Sources

(pert = 0.07, N = 48, M = 8, D = 7, f = 0.2, number of sensors per sa = 6)





Ship Tracks: 30 Minute Event

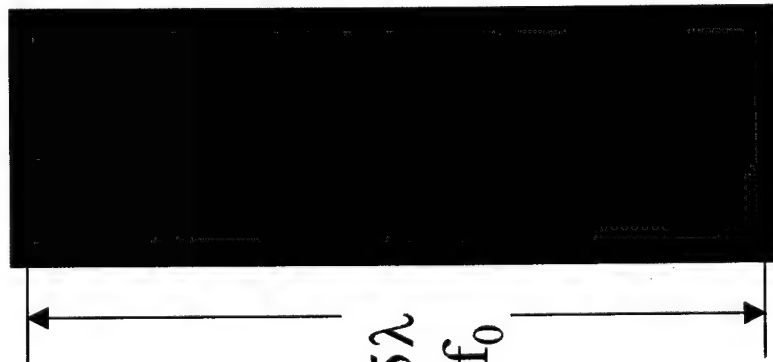




ONR Acoustic Observatory Segment ($L = 1$, $N = 48$) or ($L = 4$, $N = 192$)



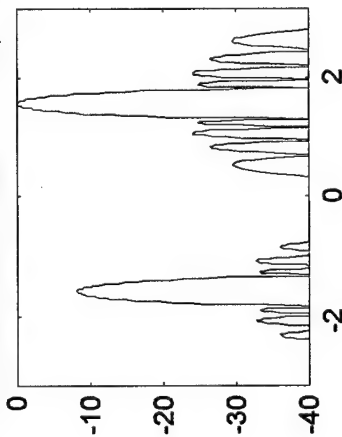
2.5λ at f_0



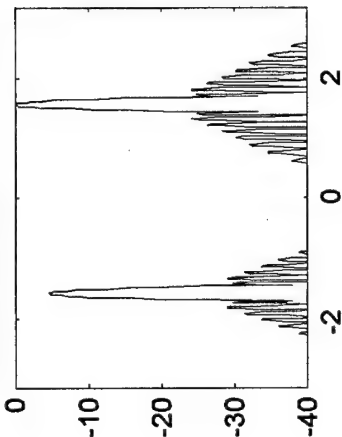
23.5λ
at f_0

$f = 1.0$ at f_0

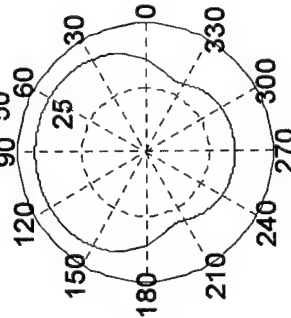
Horizontal Beam Pattern: $f = 0.2$, $s = 4$



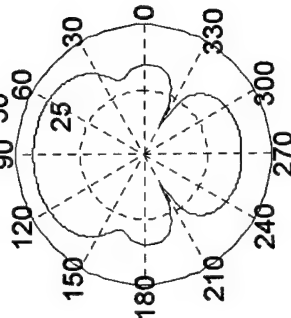
Horizontal Beam Pattern: $f = 0.4$



V B P: $f = 0.2$, shading = 4



V B P: $f = 0.4$



$\longleftrightarrow 0.2\lambda$ at $f = 0.4$ (auxiliary array 2 hyd. groups)
 $\longleftrightarrow 0.25\lambda$ at $f = 0.2$ (auxiliary array 4 hyd. groups)



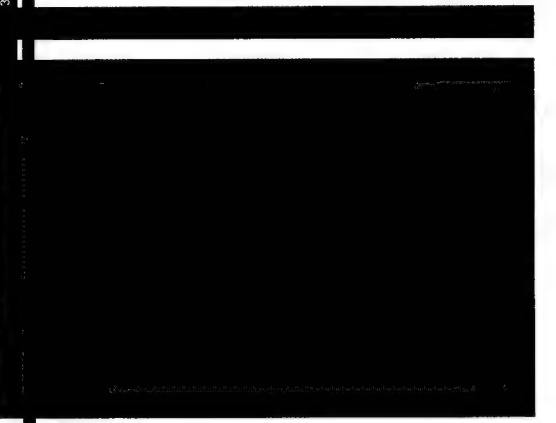
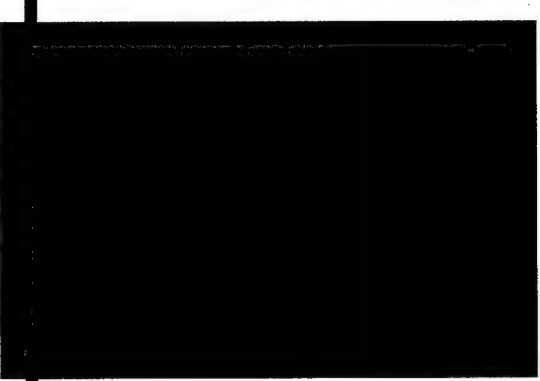
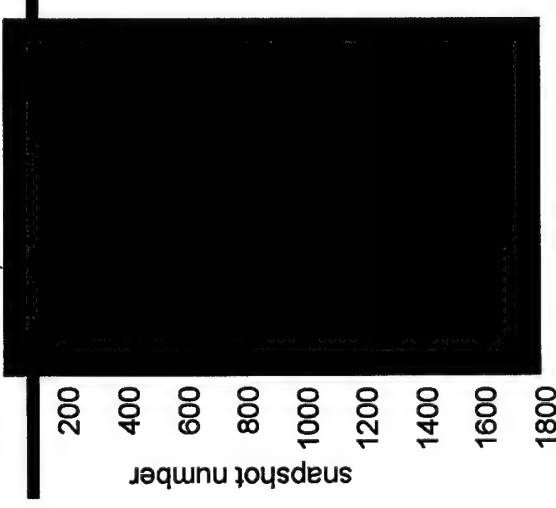
BTR Comparison: $f = 0.2$, $D = 10$ (PKE = Phase Known Exactly)

($L = 1$, $N = 48$) CBF

ES ($N_a = 48$)

SISC($N_a = 12$)

SAPP ($N_a = 12$)

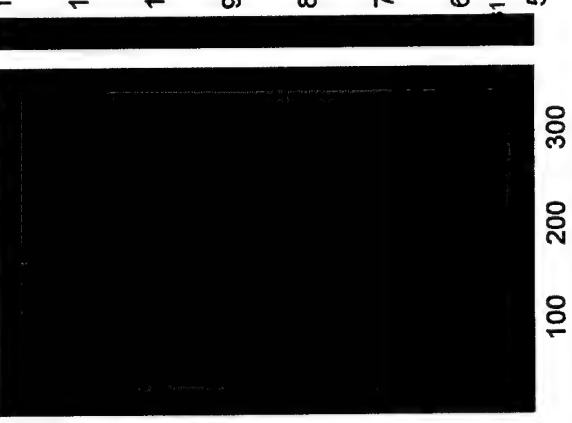
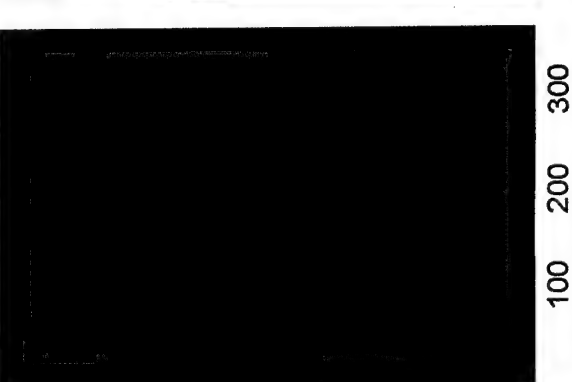
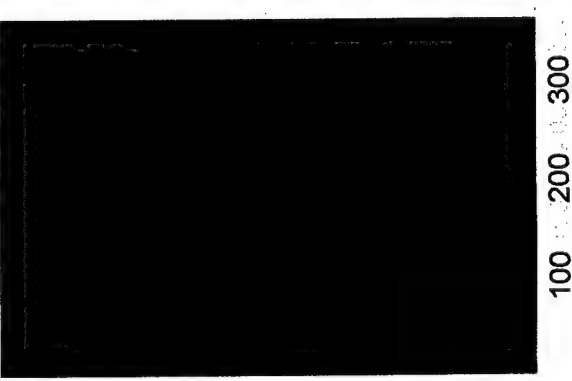
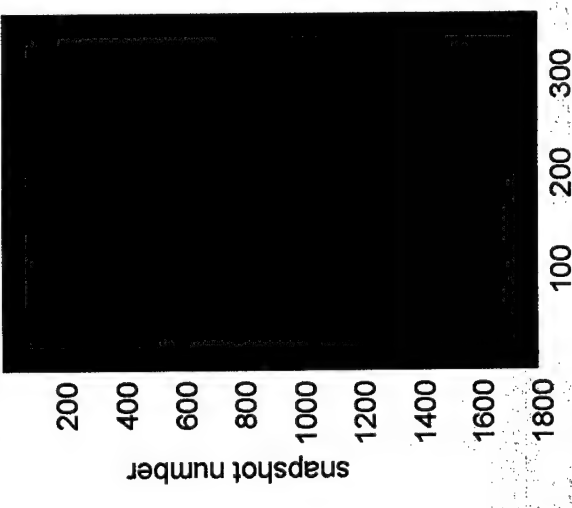


($L = 4$, $N = 192$) CBF

ES ($N_a = 192$)

SISC($N_a = 24$)

SAPP ($N_a = 48$)



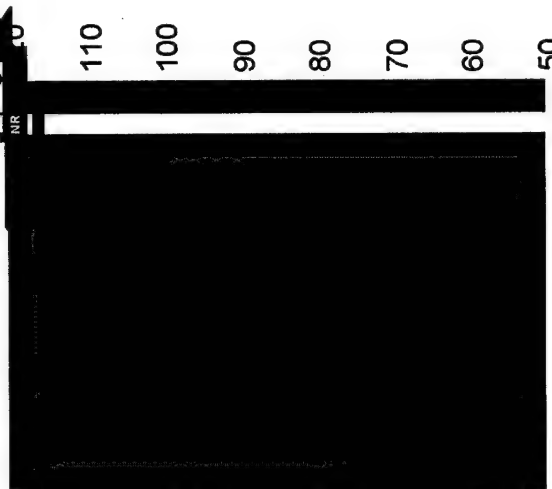
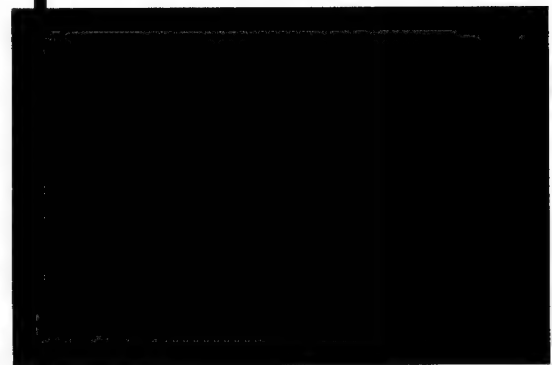
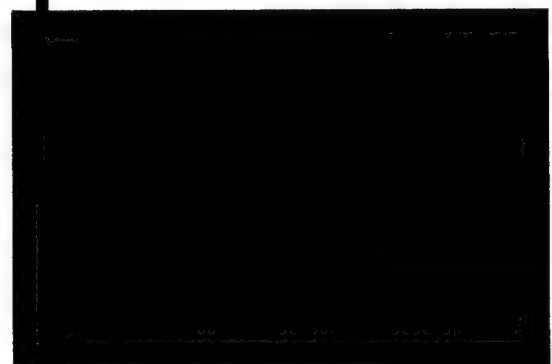
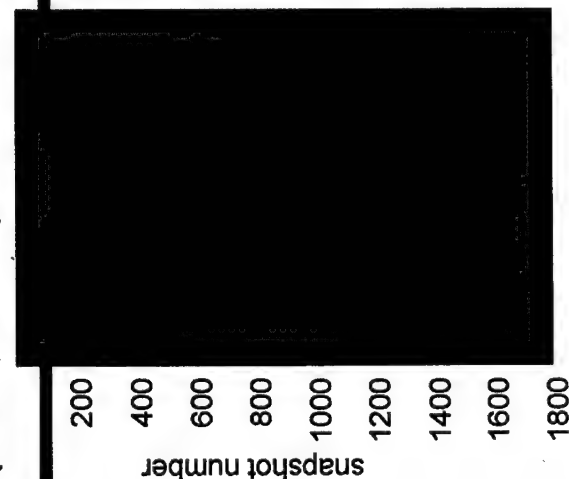
BTR Comparison: $f = 0.4$, $D = 12$ (PKE = Phase Known Exactly)

($L = 1$, $N = 48$) CBF

ES ($N_a = 48$)

SISC($N_a = 24$)

SAPP ($N_a = 24$)

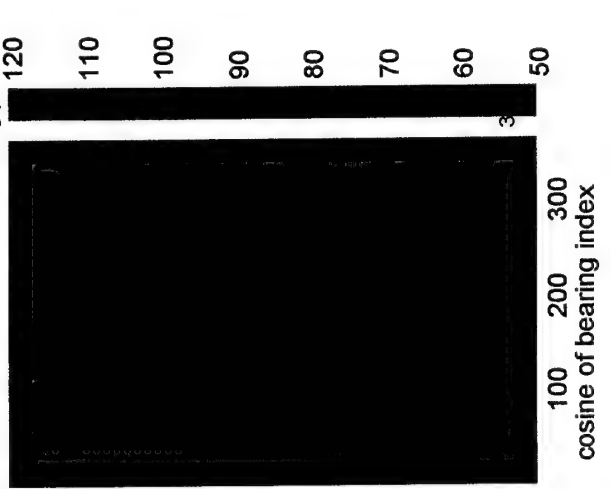
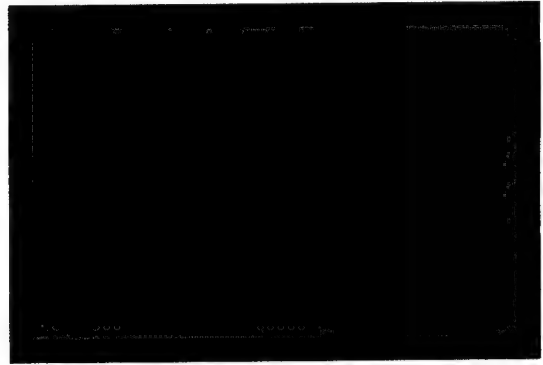
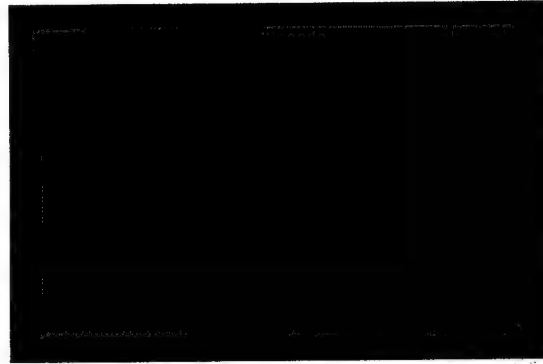
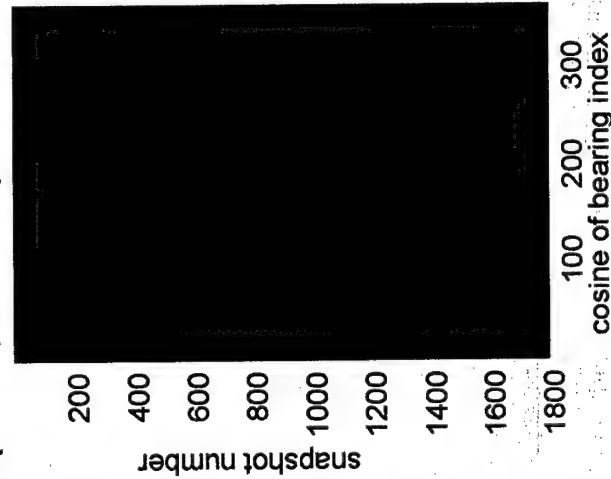


($L = 4$, $N = 192$) CBF

ES ($N_a = 192$)

SISC($N_a = 48$)

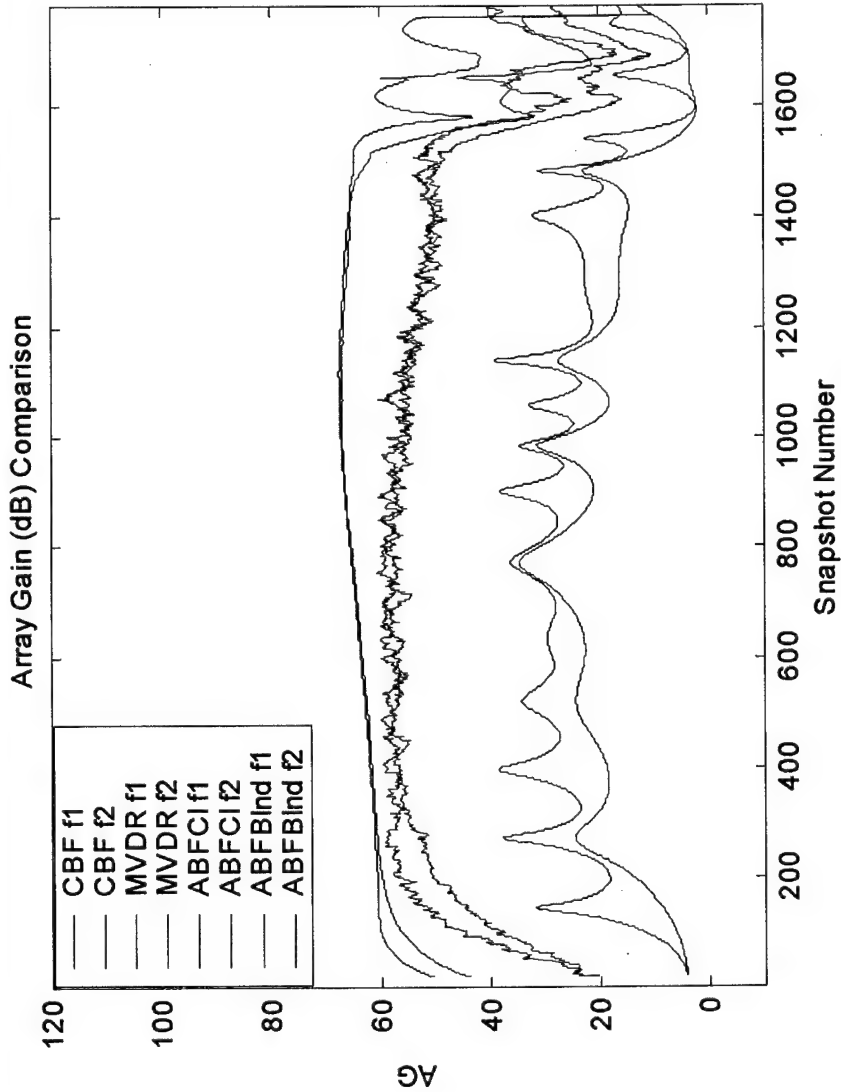
SAPP ($N_a = 96$)





AG ES DMR: N = 48, D = 10/12

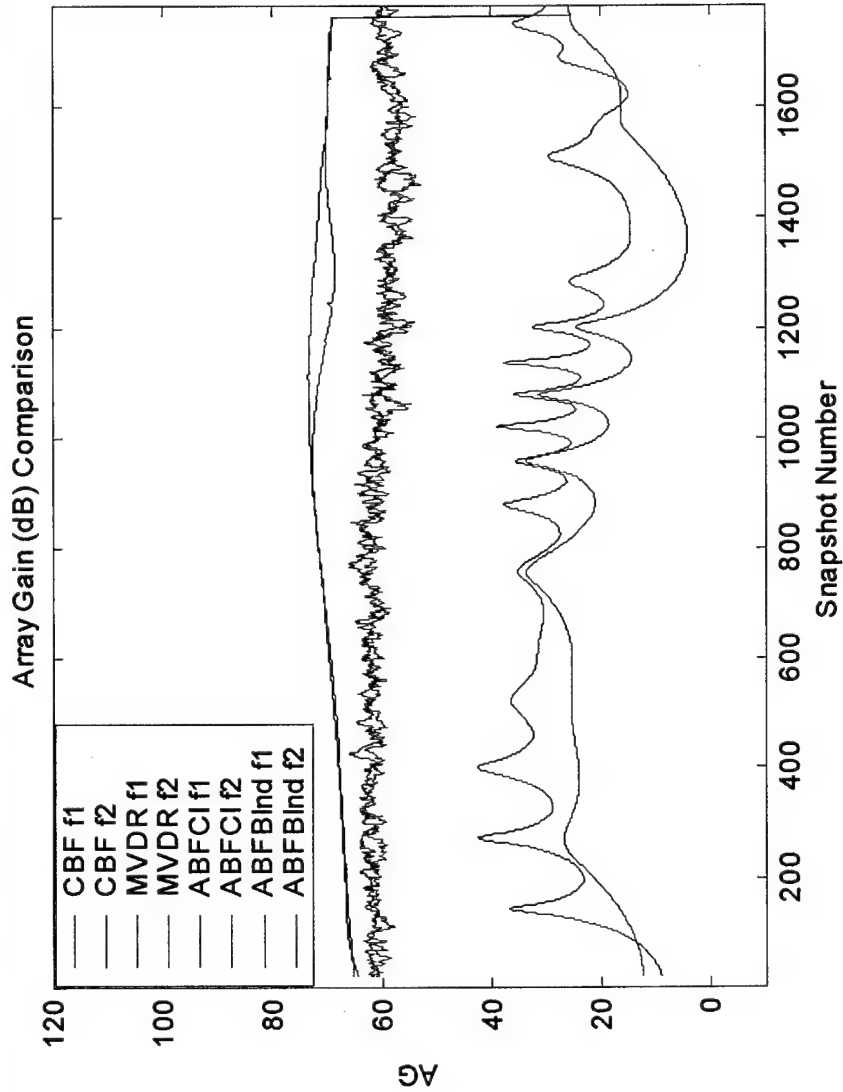
(PKE WNGC = 12 db)

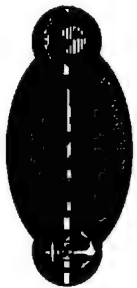




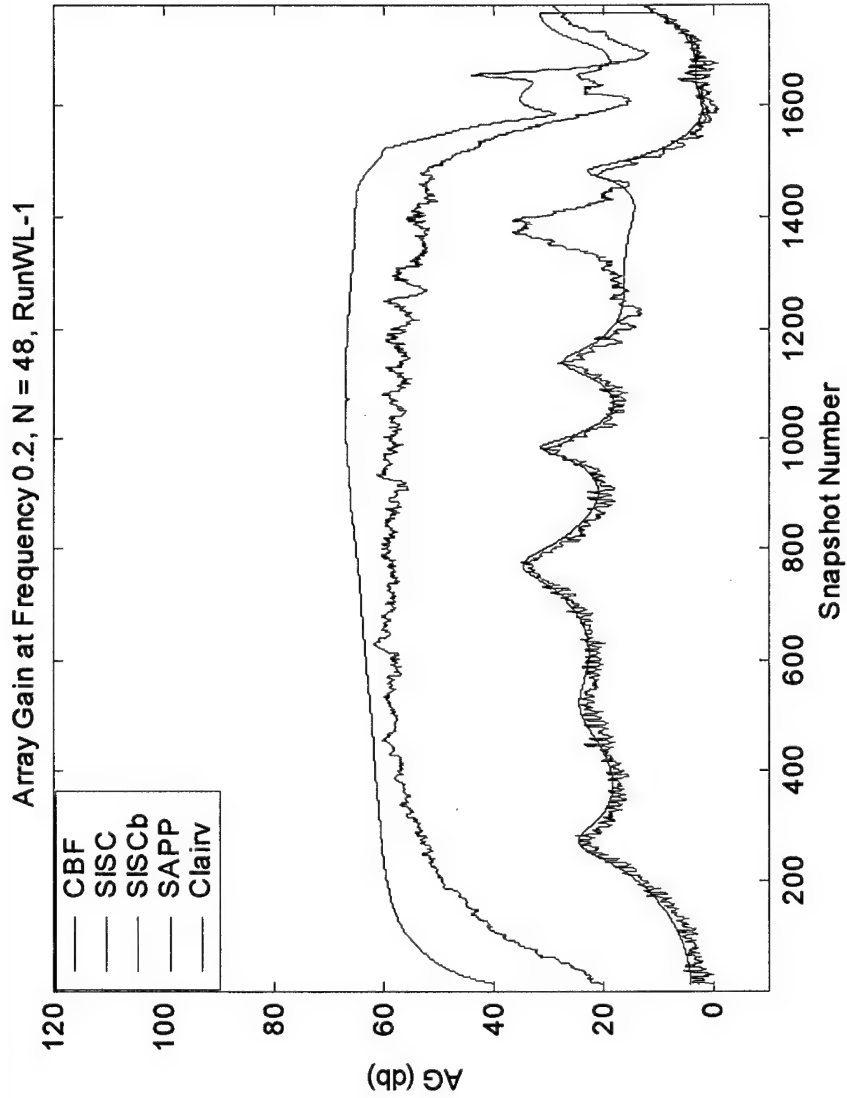
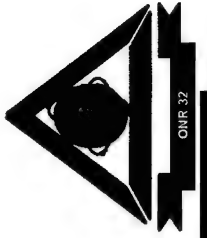
AG ES DMR: N = 192, D = 10/12

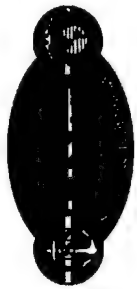
(PKE WNGC = 12 db)



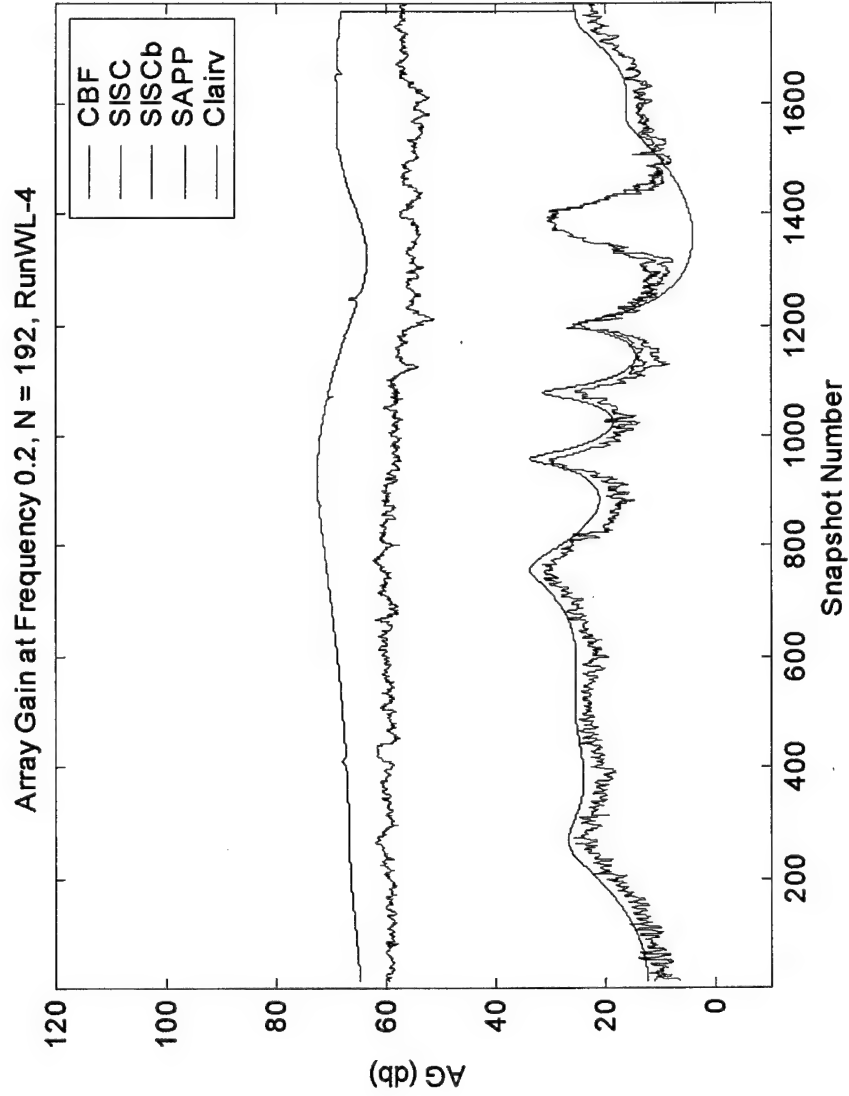


AG DMR: $f = 0.2$, $N_a = 12$, $D = 10$ (PKE)



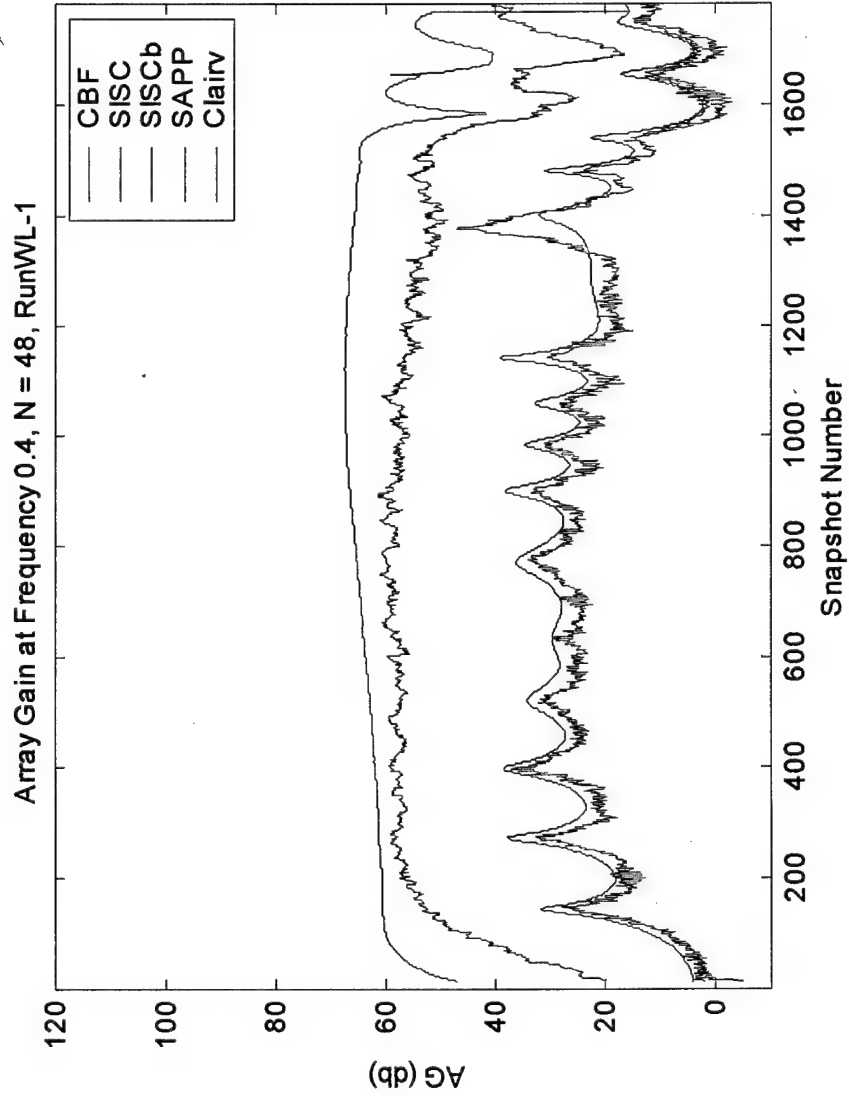


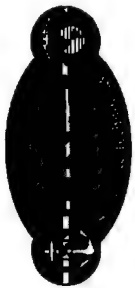
AG SA/SC DMR: $f = 0.2$, $N = 192$, $D = 10/12$ (PKE)



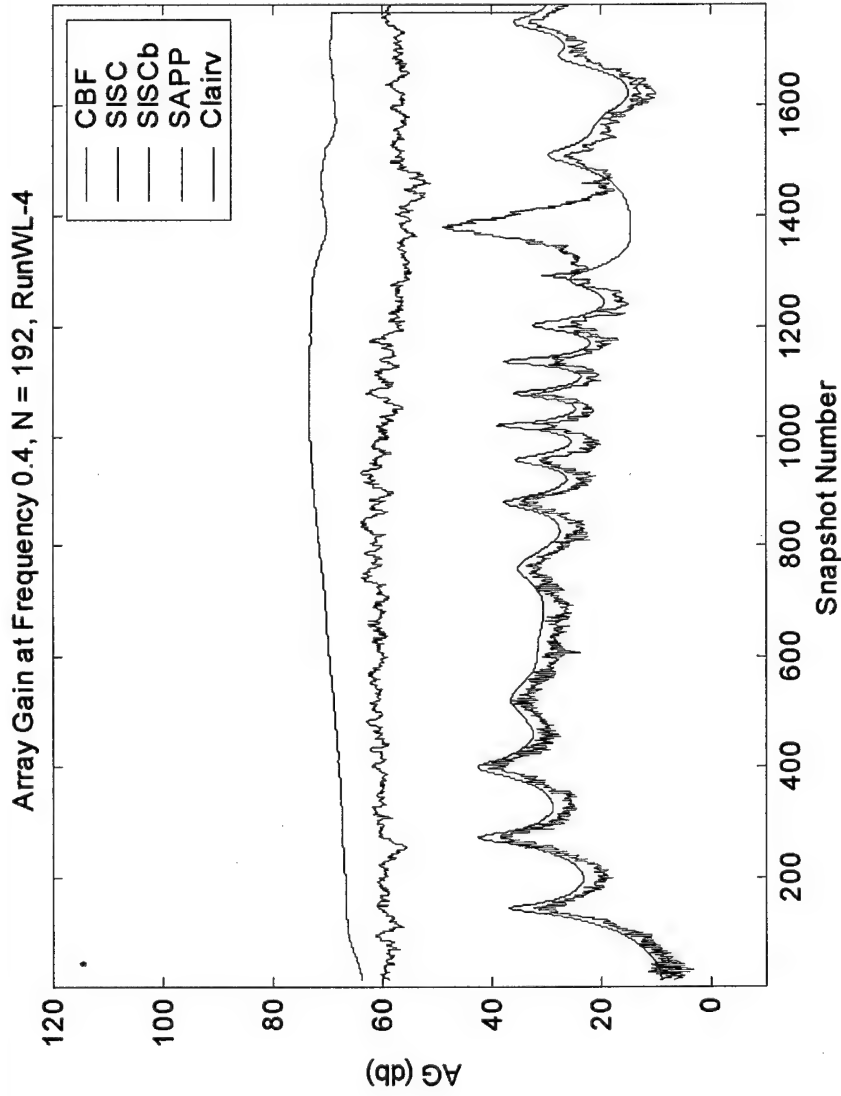


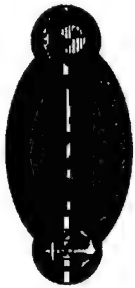
AG DMR: $f = 0.4$, $N_a = 24$, $D = 12$ (PKE)



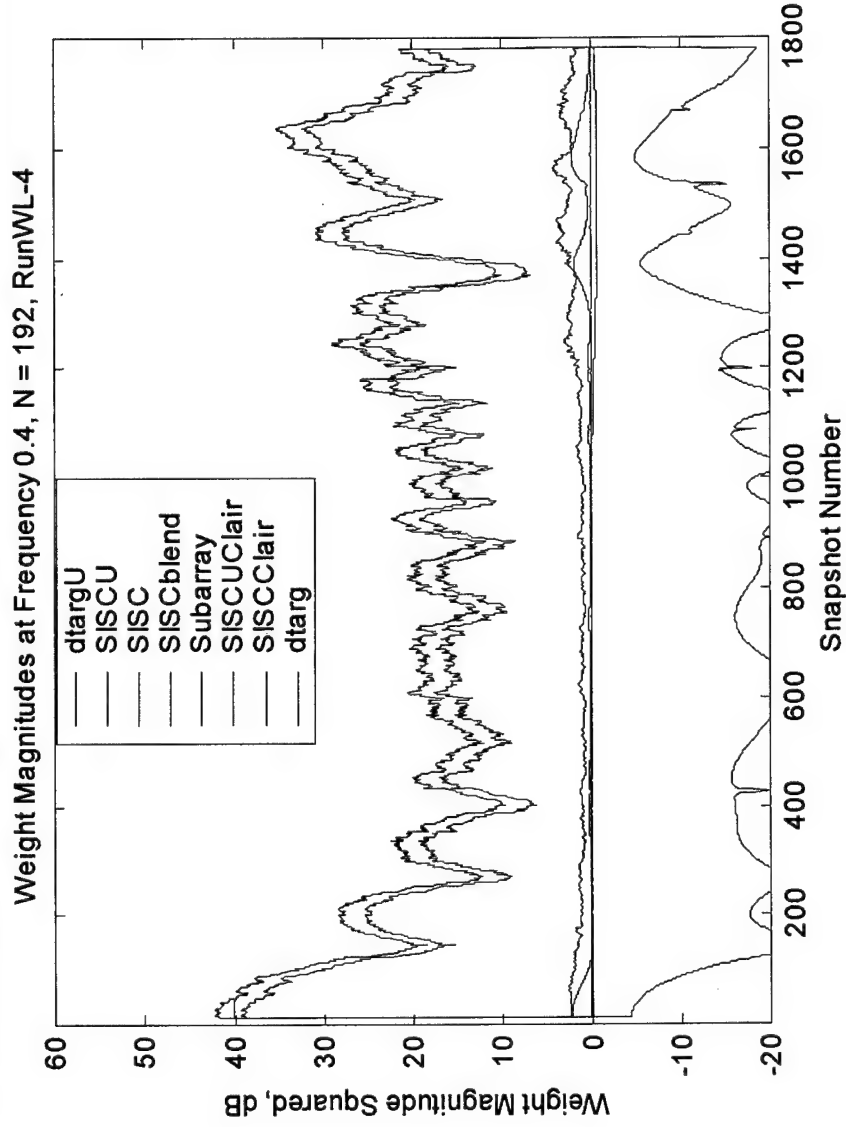


AG SA/SC DMR: $f = 0.4$, $N = 192$, $D = 10/12$ (PKE)





Clue to SISC AG Degradation: Stochastic v. Clairvoyant Weight Vector MS





Final Comments



Candidate ABF spaces for efficient DMR ABF:

Beam, subarray, auxiliary (sparseness is key)

Adaptation space sample vector should/can be independent of beam steering direction and have N_a order $O(D + \text{safety factor})$.

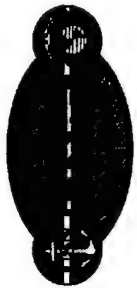
The Steering Invariant Sidelobe Canceller (SISC) is an auxiliary space method that can “hedge” on the spatial sampling theorem and increase efficiency. AG is an open issue.

“Measure” the need for ABF at higher frequencies.

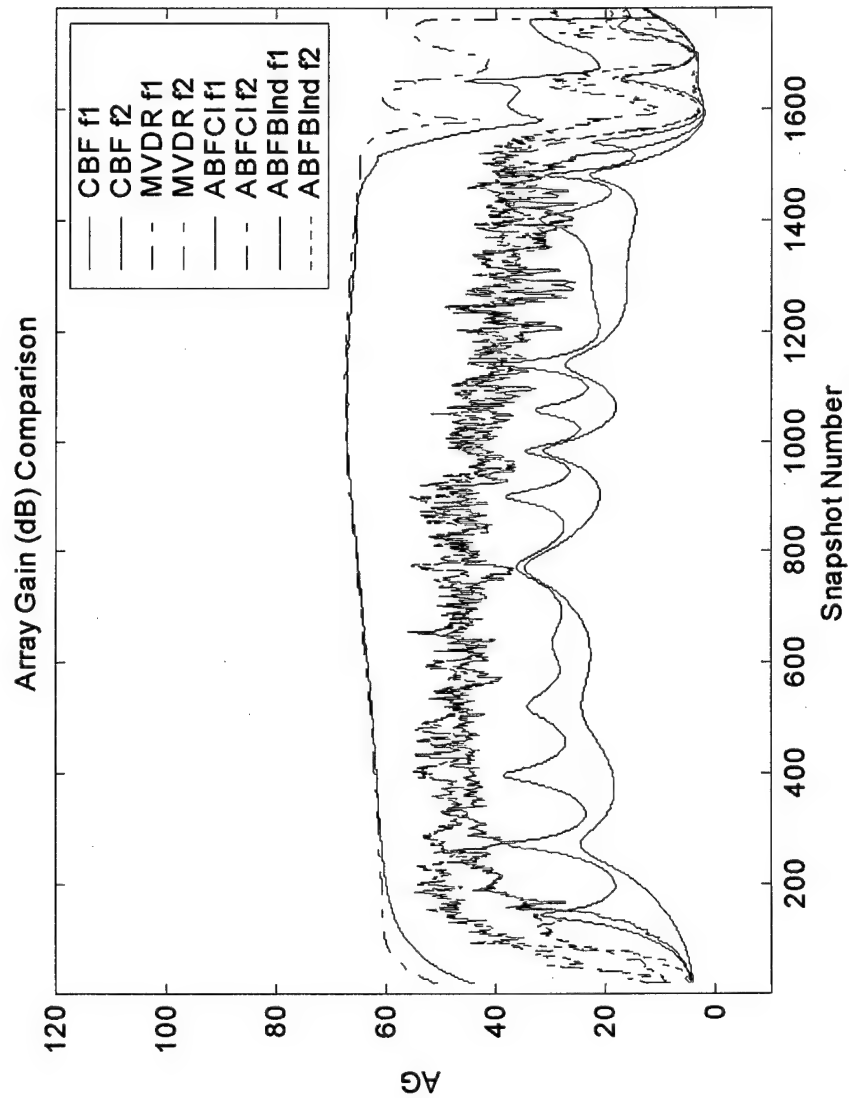
Signal Suppression v. Spatial Resolution: Clairvoyant ABF without an infinite number of beams suppresses loud sources but, by definition, produces “the best” spatial resolution.



BACKUP



AG ES DMR: N = 48, D = 10/12 (2 degree phase pert)





Session V: Sonar I (Classified)



ONR 32

Adaptive Beamforming with the T-16 Array for Broadband Detection

H. Cox/ Orincon Corporation
S. Kogon/ MIT Lincoln Laboratory
H. Lai/ Orincon Corporation
T. Phipps/ UT ARL

Adaptive Array Processing for the MK-48 Torpedo in a Shallow Water Countermeasure Scenario

A. Mirkin/ NUWC
N. Pulsone/ MIT Lincoln Laboratory

An Adaptive Beamformer for Spectrum Analysis in Passive Sonar Systems

S. Kogon/ MIT Lincoln Laboratory
K. Arsenault/ MIT Lincoln Laboratory

Sub-Aperture Beamspace Adaptive Array Processing

H. Freese/ SAIC
B. Sperry / SAIC
K. Votaw/ / SAIC



Session V: Sonar I - Themes



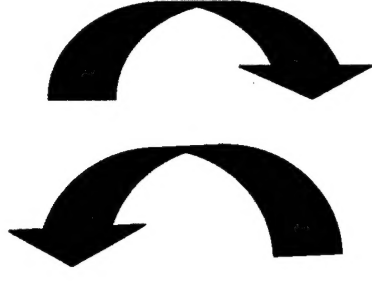
Detection v. Classification in Clutter

ABF for Detection in Clutter

- Spatial resolution is key
- Aggressive/minimally constrained BB ABF
- High SNR signal suppression is acceptable

ABF for Classification in Clutter

- Minimum spectral distortion is key
- Highly constrained mainlobe ABF
- Must balance rejection of undesired interference in the beam with suppression of desired signal in the same beam

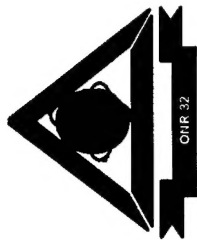


Rapid Adaptivity

- Reverberation, shipping dynamics, array motion and high data dimensionality



Shipping Parameters



OHR 32

Number of sources = 8

Source SoA = 1.5 knts.

Source SoA = 4.1 knts.

Source SoA = 8.2 knts.

Source SoA = 6.8 knts.

Source SoA = 7.5 knts.

Source SoA = 6.8 knts.

Source SoA = 0.5 knts.

Source SoA = 0.3 knts.

Source Level Range(wl) Prop Loss Amb Level SNR SoA(wl/s) Heading (SourceInfo = 1.0e+003 *)

0.1000	0.7018	0.0569	0.0600	-0.0169	0.0015	0.0800
0.1650	2.0000	0.0660	0.0600	0.0390	0.0041	0.1800
0.1700	3.1623	0.0700	0.0600	0.0400	0.0082	0
0.1500	3.3601	0.0705	0.0600	0.0195	0.0068	0
0.1650	4.4721	0.0730	0.0600	0.0320	0.0075	0.0450
0.1600	2.9547	0.0694	0.0600	0.0306	0.0068	0
0.1200	1.8601	0.0654	0.0600	-0.0054	0.0005	0.0300
0.1250	1.7205	0.0647	0.0600	0.0003	0.0003	0.0450

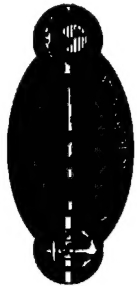
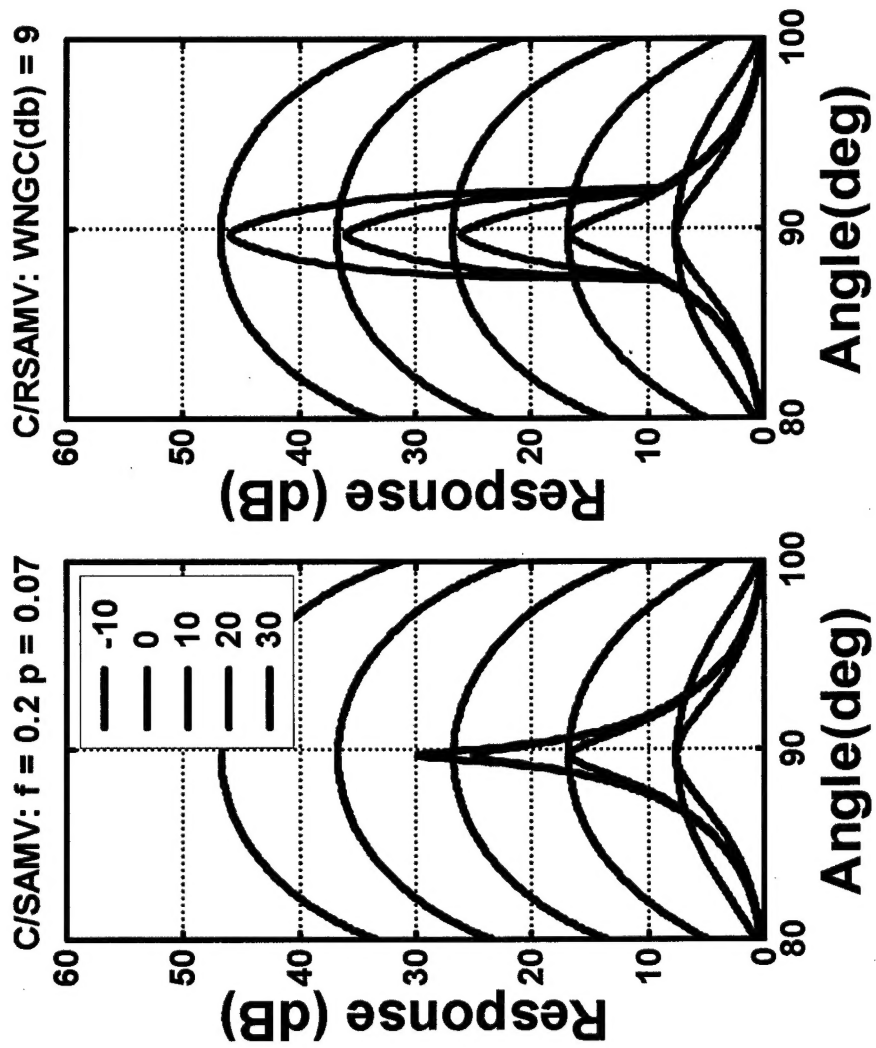


Figure 3.4





Six Stationary Sources

($\text{pert}=0.07$, $D=7$, $N=48$, $M=12$, $f=0.2$, $\text{sa group size}=4$)

